Dark matter in the Sun and stars

Aaron Vincent

Dark Side of the Universe | UNSW Sydney | December 6 2022

Queen's University

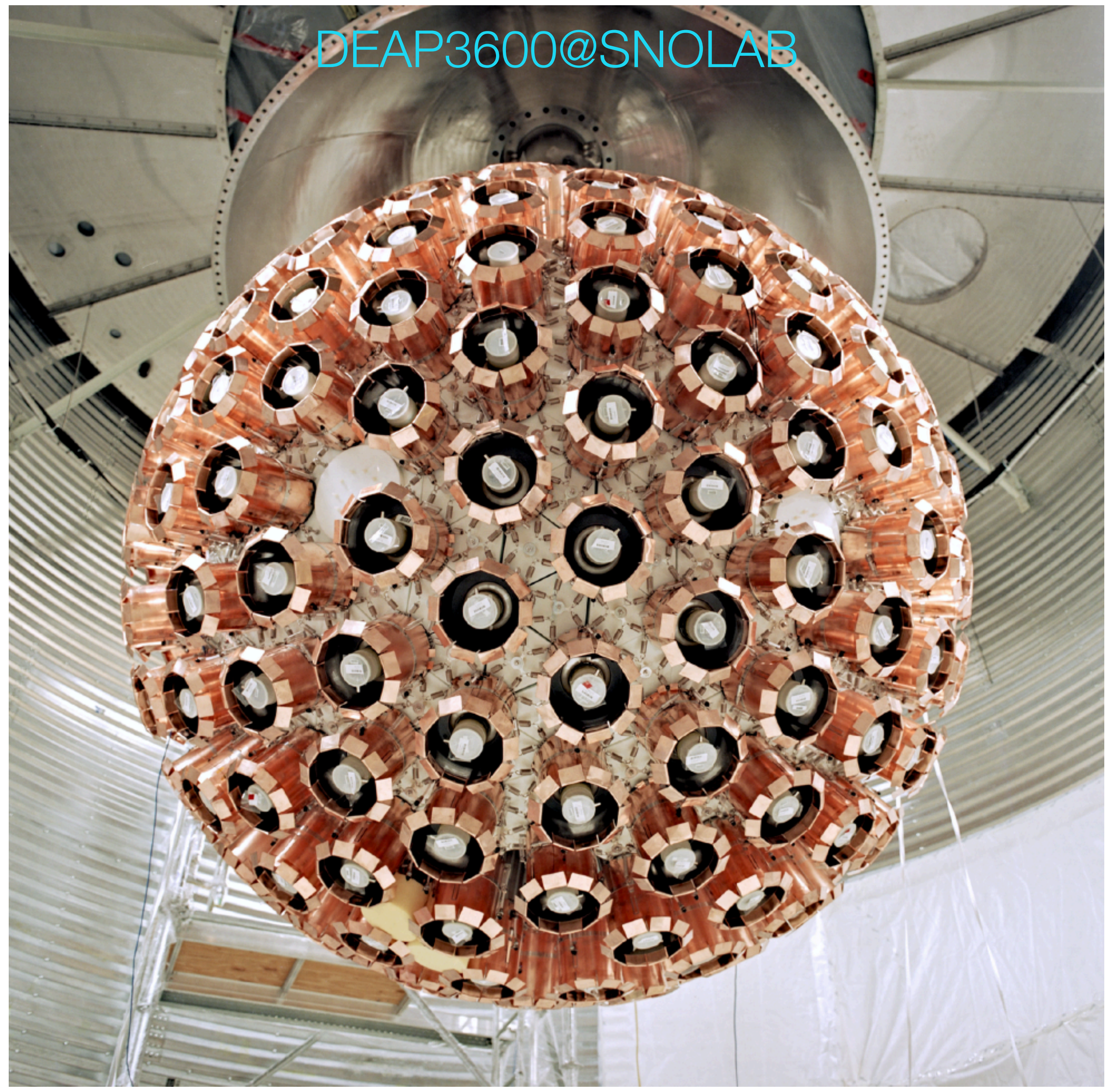
Centre Canadien de Recherche en Physique des Astroparticules

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

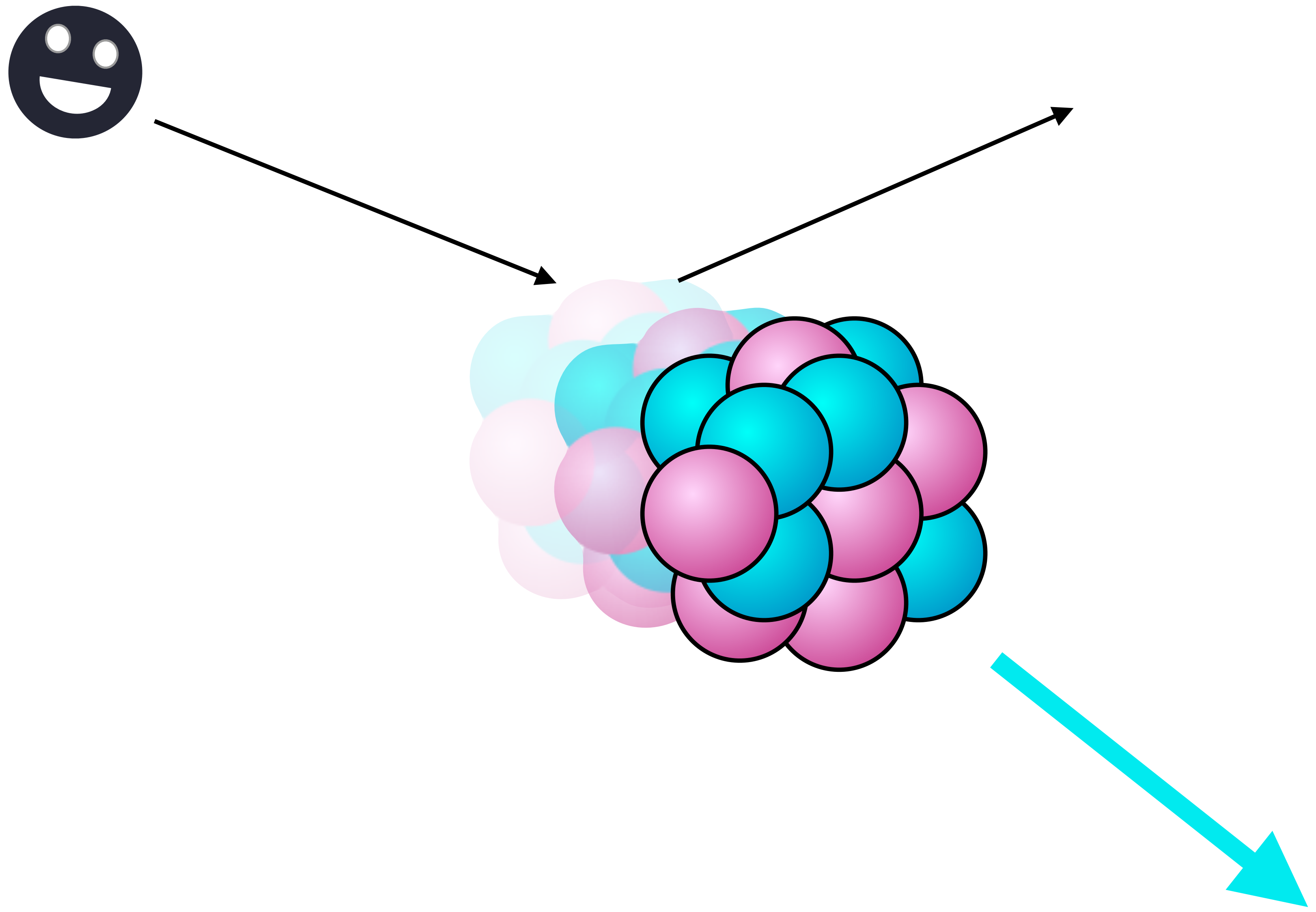
Plan

1. Dark matter in main(ish) sequence stars
2. Refining the theory
3. Precision theory and measurements & the future of dark matter in stars

Direct detection of dark matter

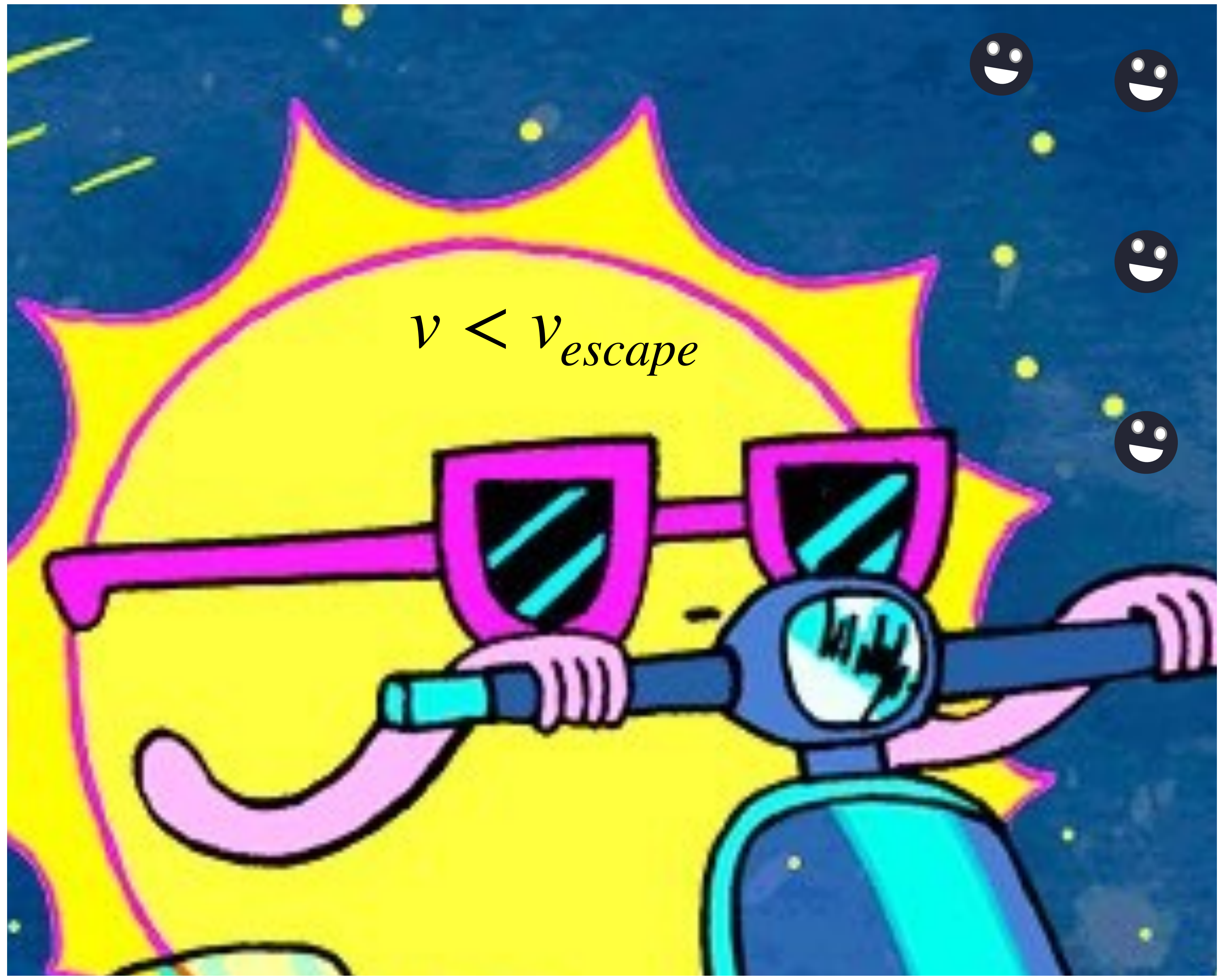


Detector full of target material
Shielded deep underground
Low backgrounds



Most sensitive to **heavy**, **fast** particles → larger recoil signal
Signal ∝ detector mass (now ~ 1000 kg)

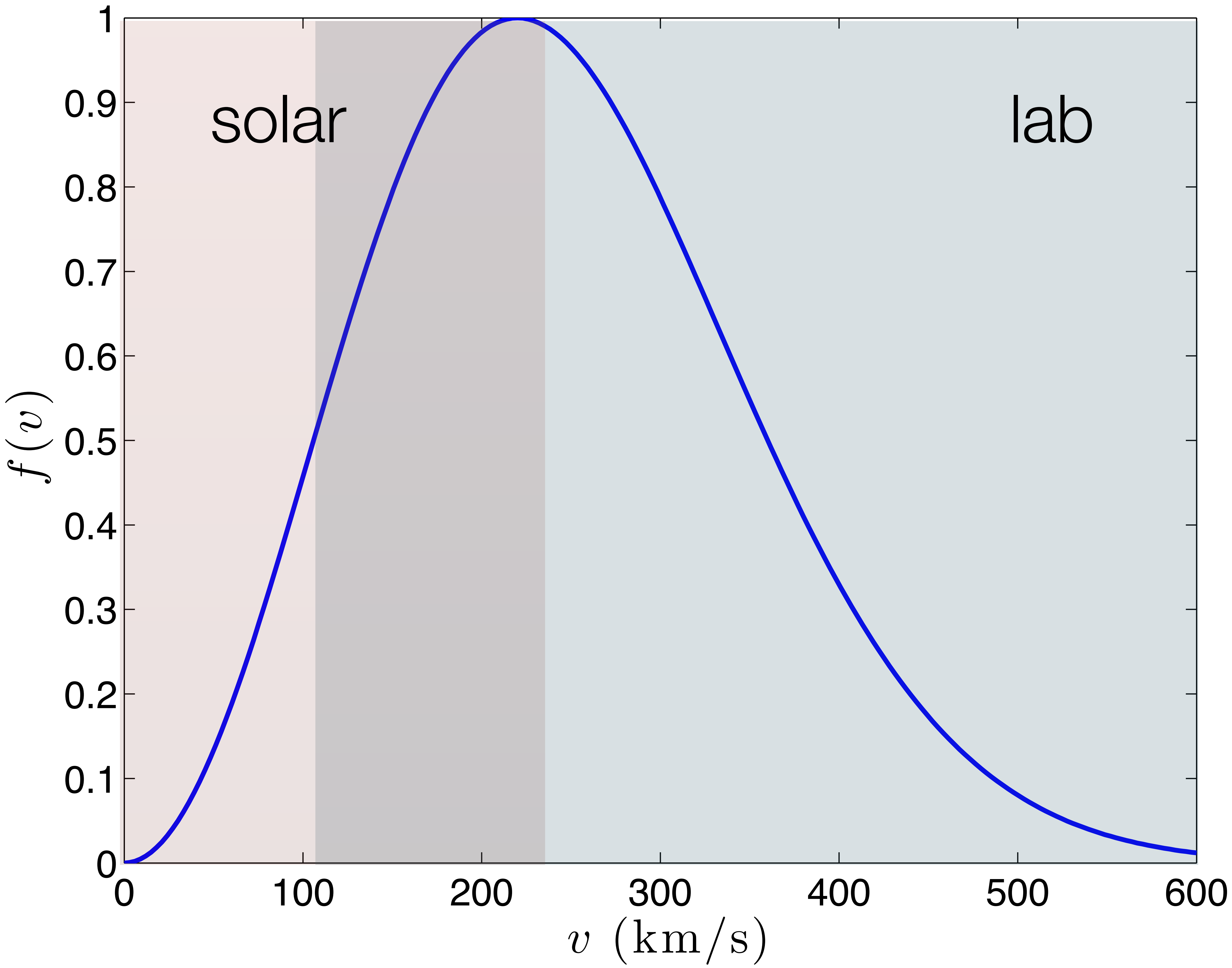
The sun is a direct detection experiment



DM scatters with nuclei, losing kinetic energy & becoming gravitationally bound

- $M = 2 \times 10^{30}$ kg
- 73% Hydrogen
- 25% Helium
- 2% Heavier elements (important since $\sigma_{SI} \propto A^2$)
- Not supercooled: need to be clever about "readout"

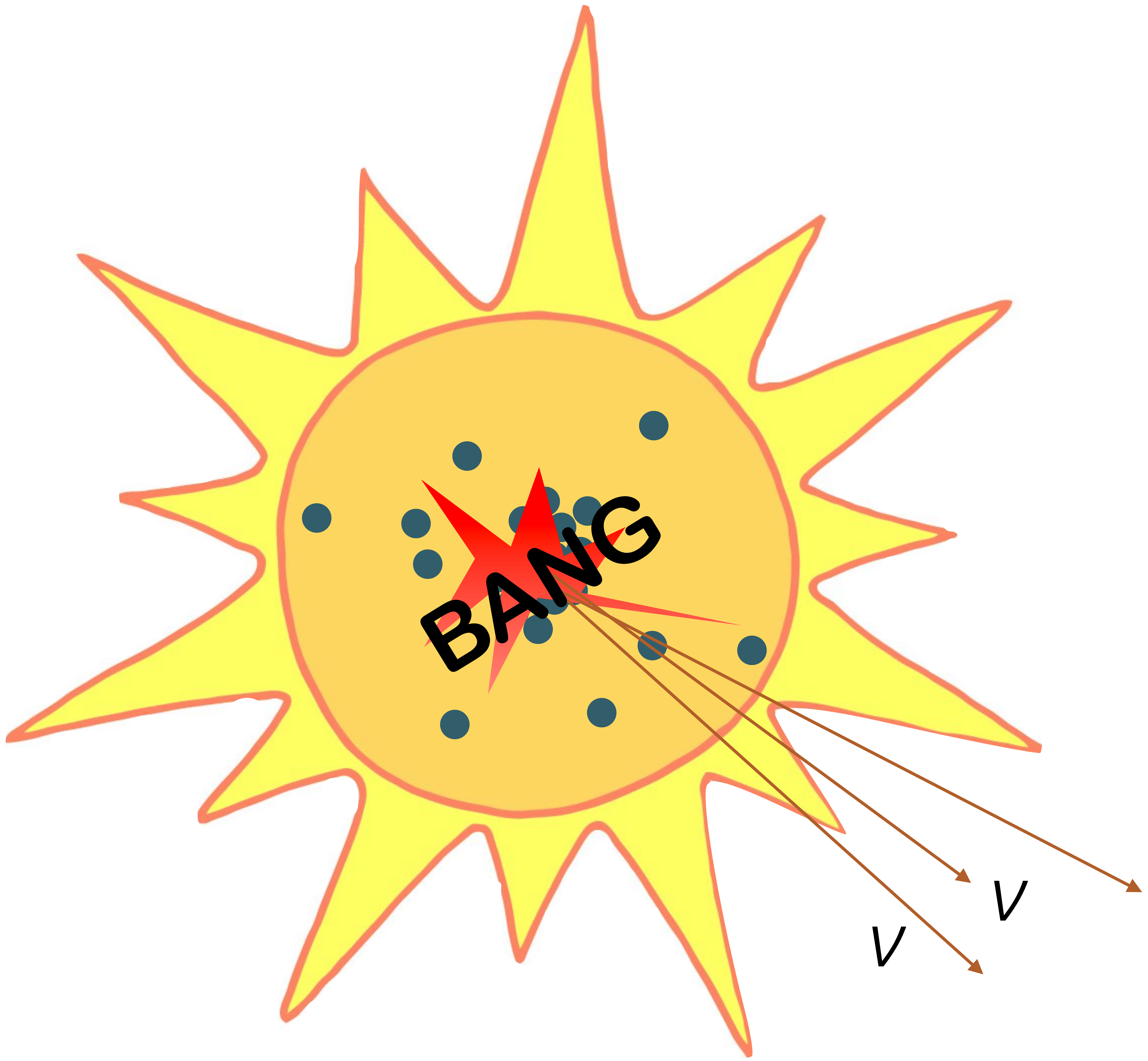
Differences with earth-based detection

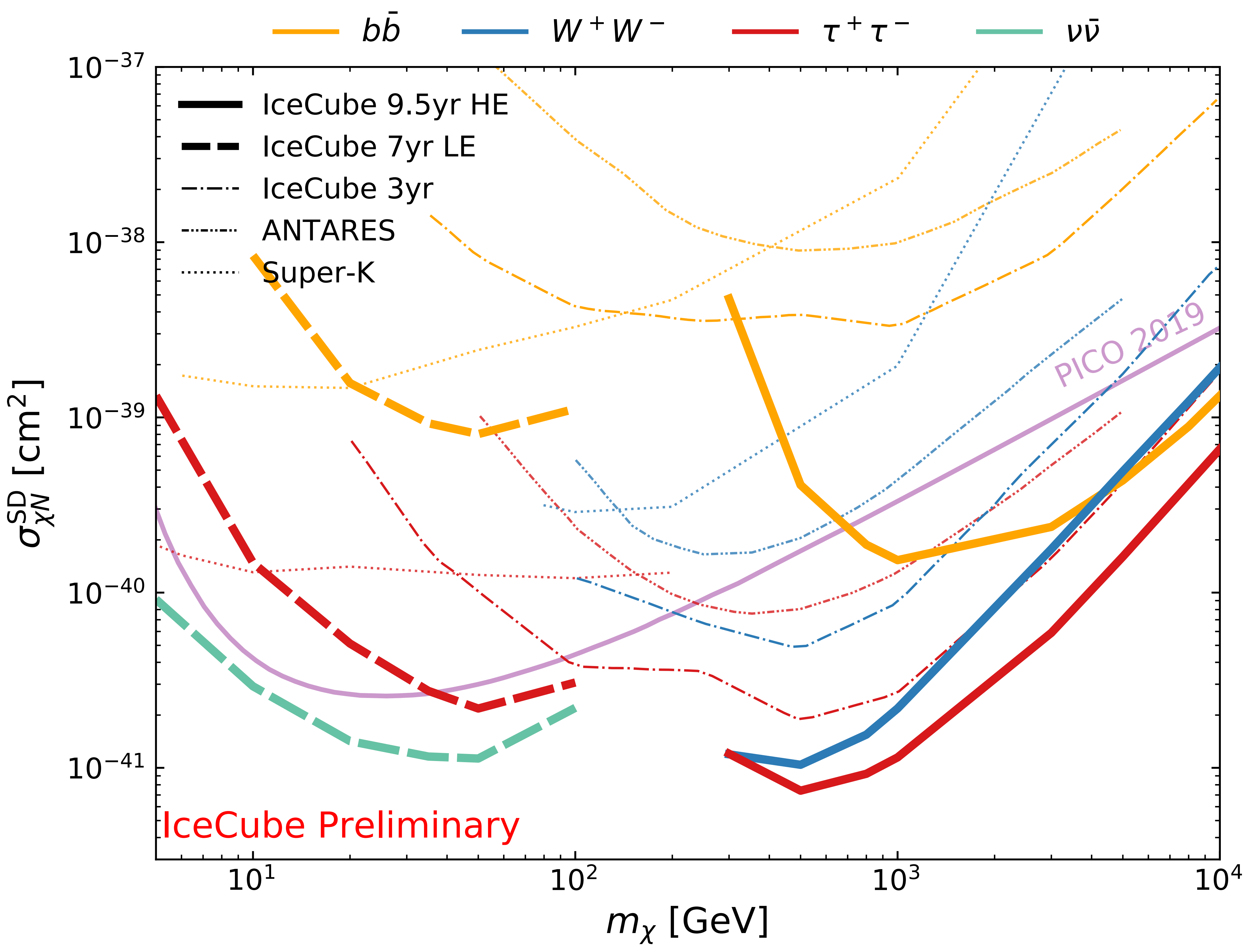


Sun more sensitive to lighter DM

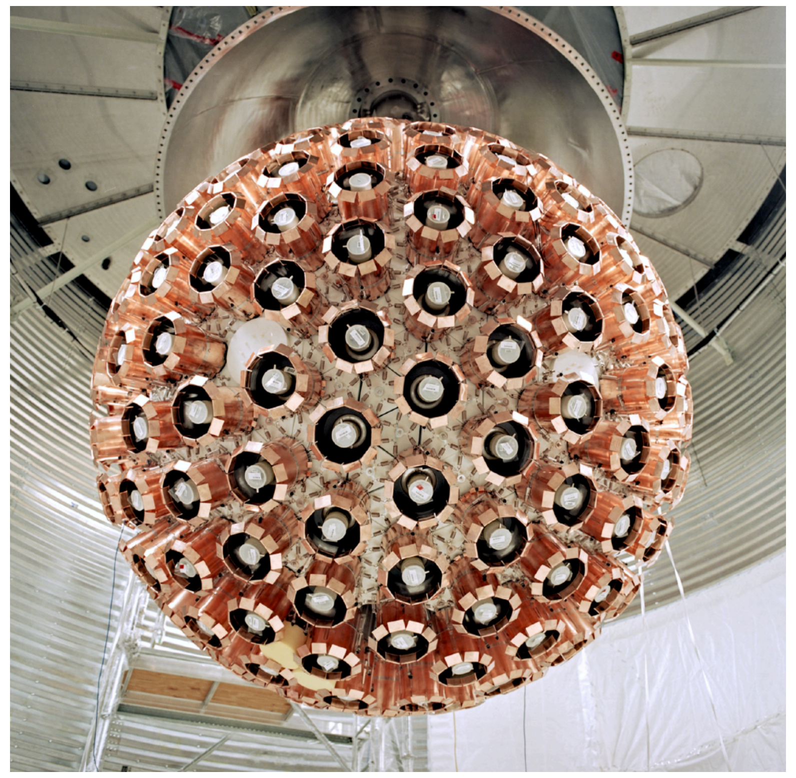
Sensitive to different particle couplings, e.g. $\sigma \propto q^n$

If DM annihilates: look for neutrinos





Global fit with GAMBIT



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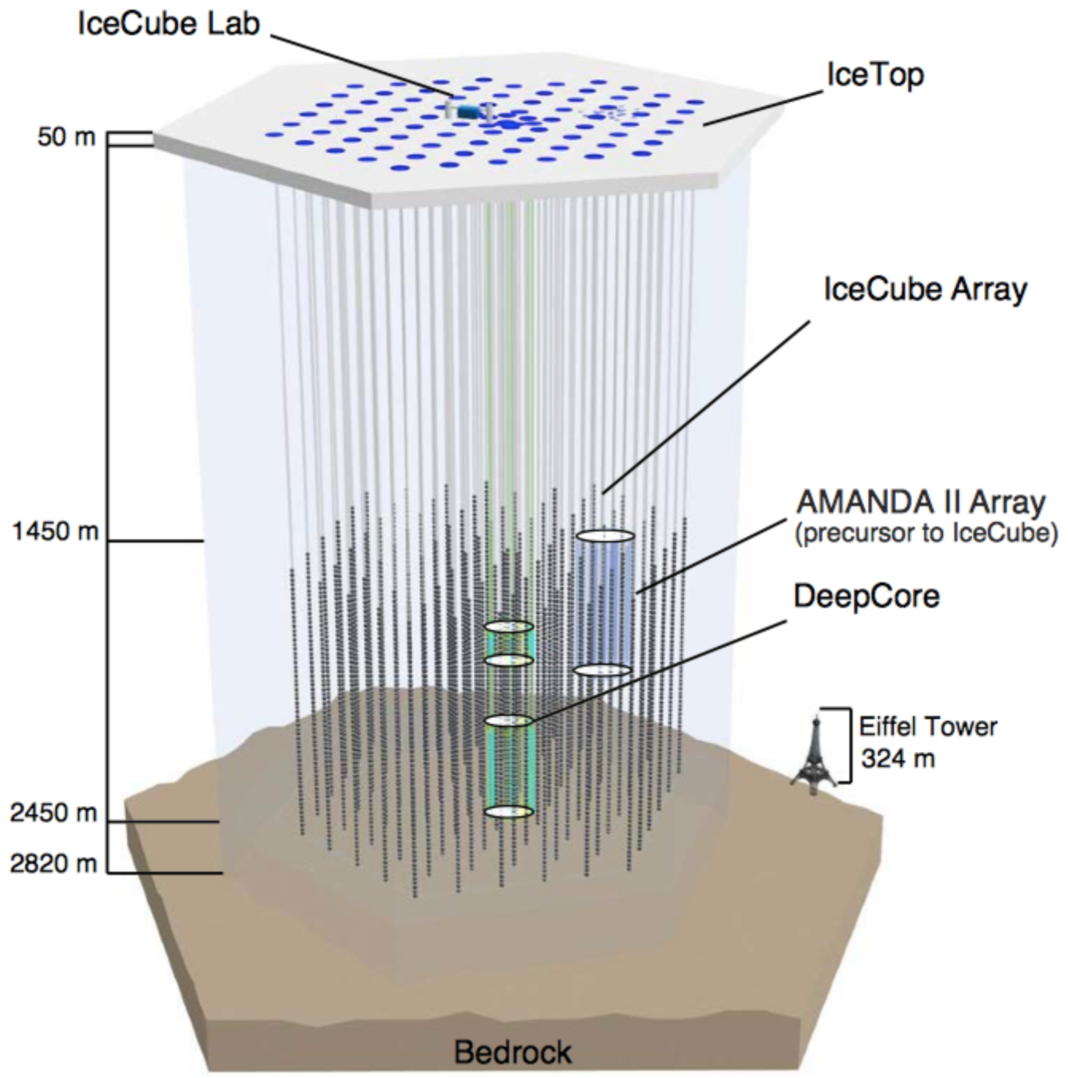
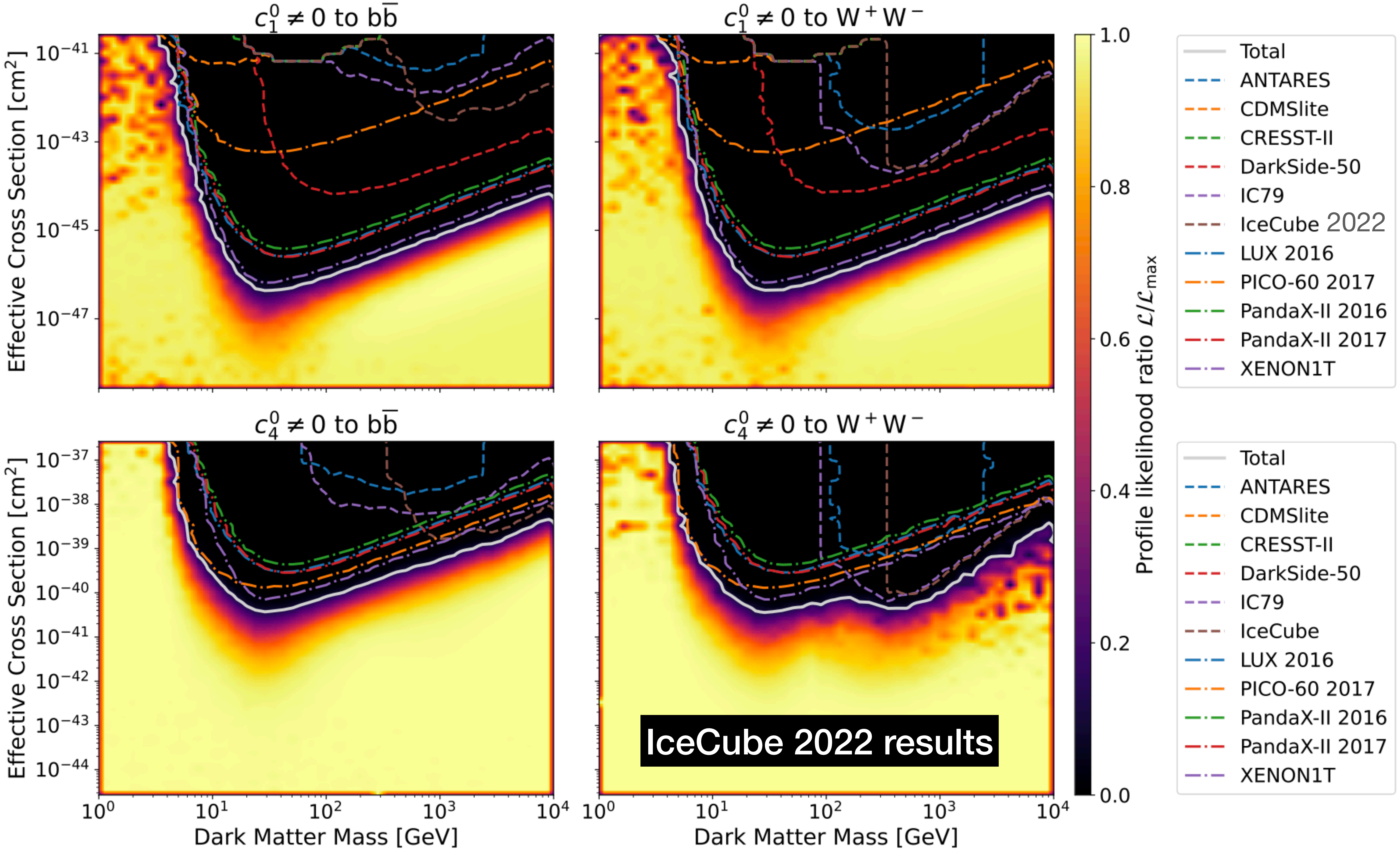




Avis Kozar, Scott, ACV *in prep*

(shameless plug)

For more GAMBIT goodness, see these talks:

Chris Chang Tuesday @ 16:50 (Dark Matter) Global Fits of vector-mediated simplified models for Dark Matter

Ankit Beniwal Thursday @ 15:00 (Dark Matter) Thermal WIMPs and the Scale of New Physics

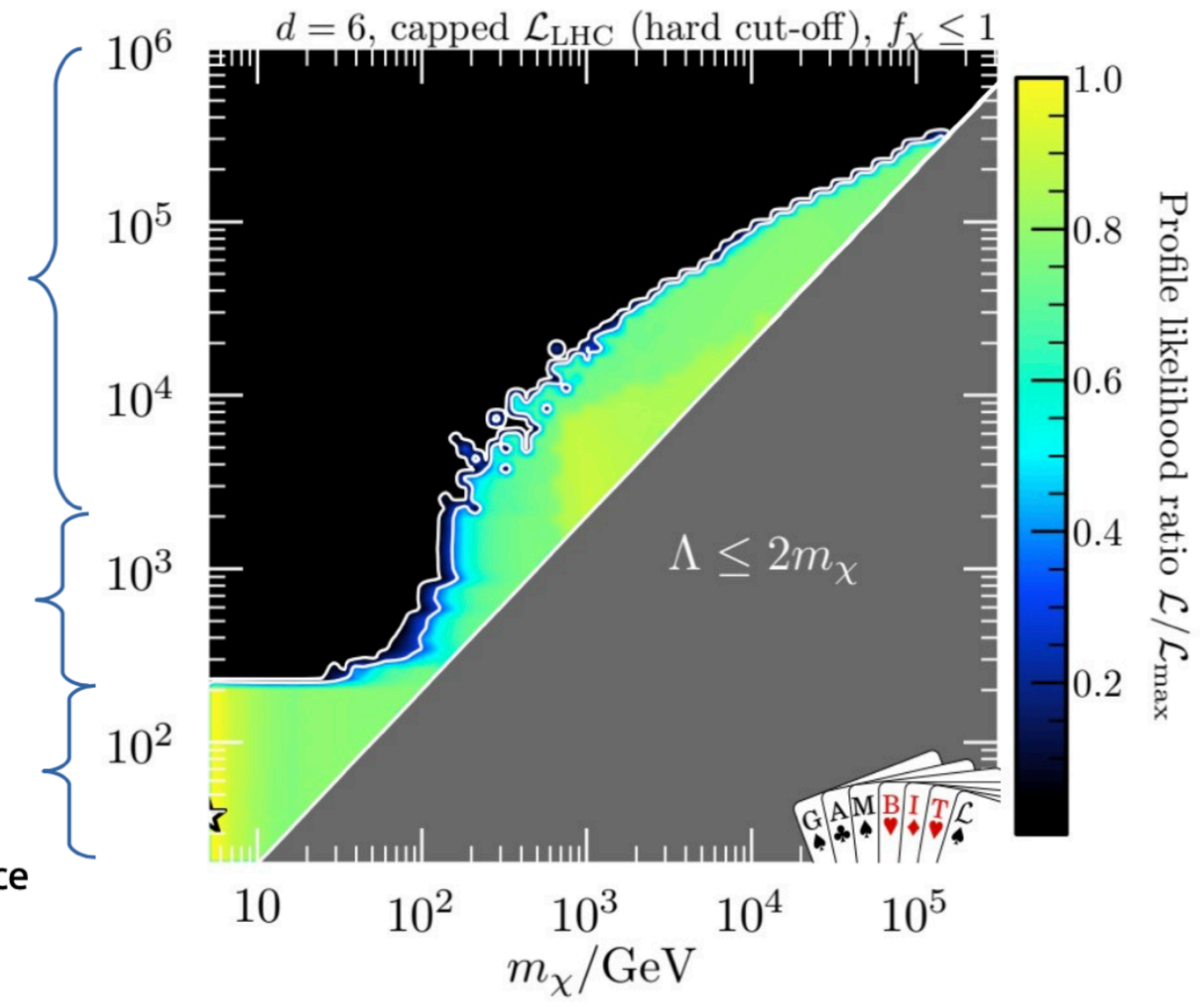
Csaba Balazs Friday @ 11:30 (Plenary) Dark Matter with GAMBIT

New physics scale Λ:

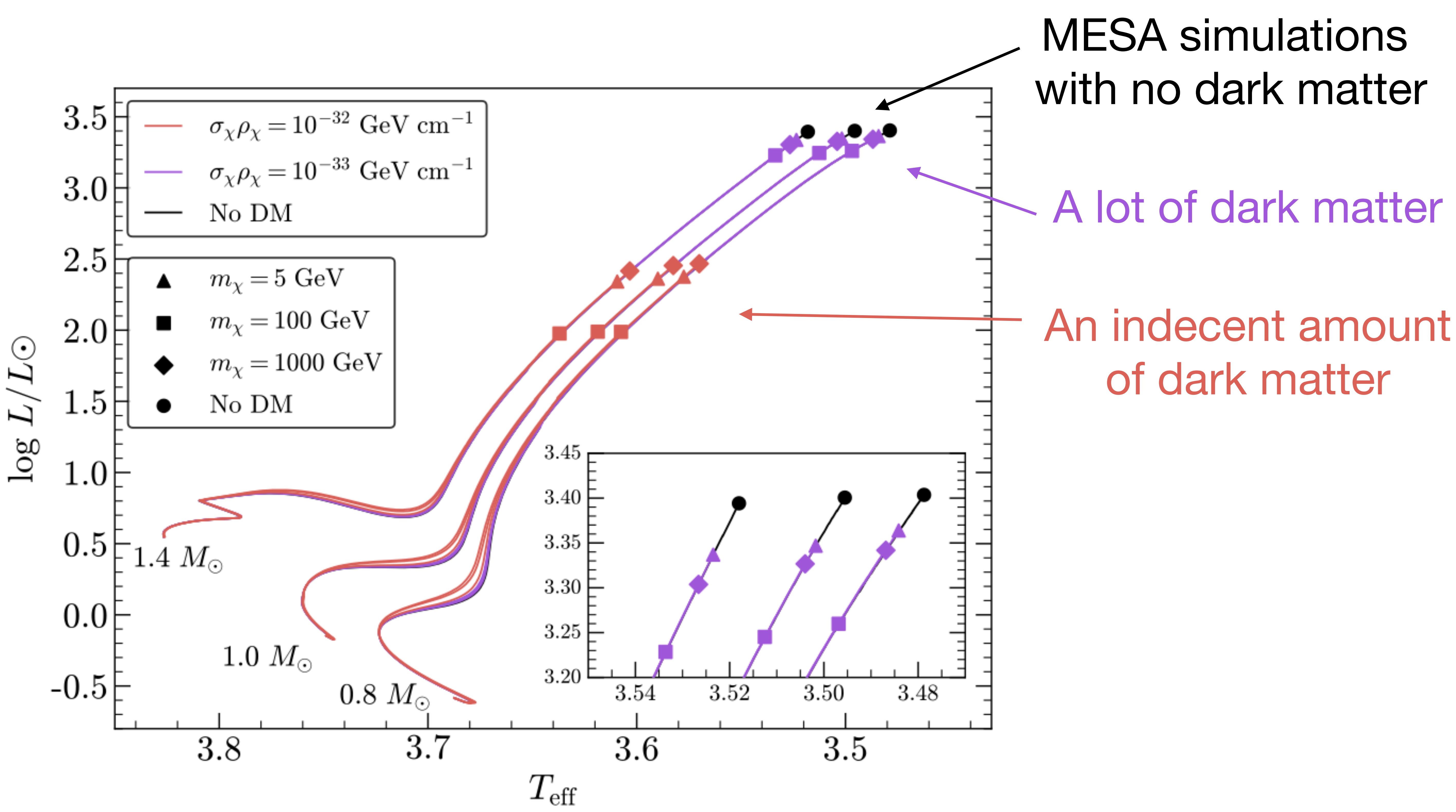
- EFT valid for all constraints
- Most experiments are insensitive
- Constraints driven by relic density requirement

- Λ comparable to LHC energies
- Strong LHC constraints

- Λ below LHC energies
- Large viable parameter space



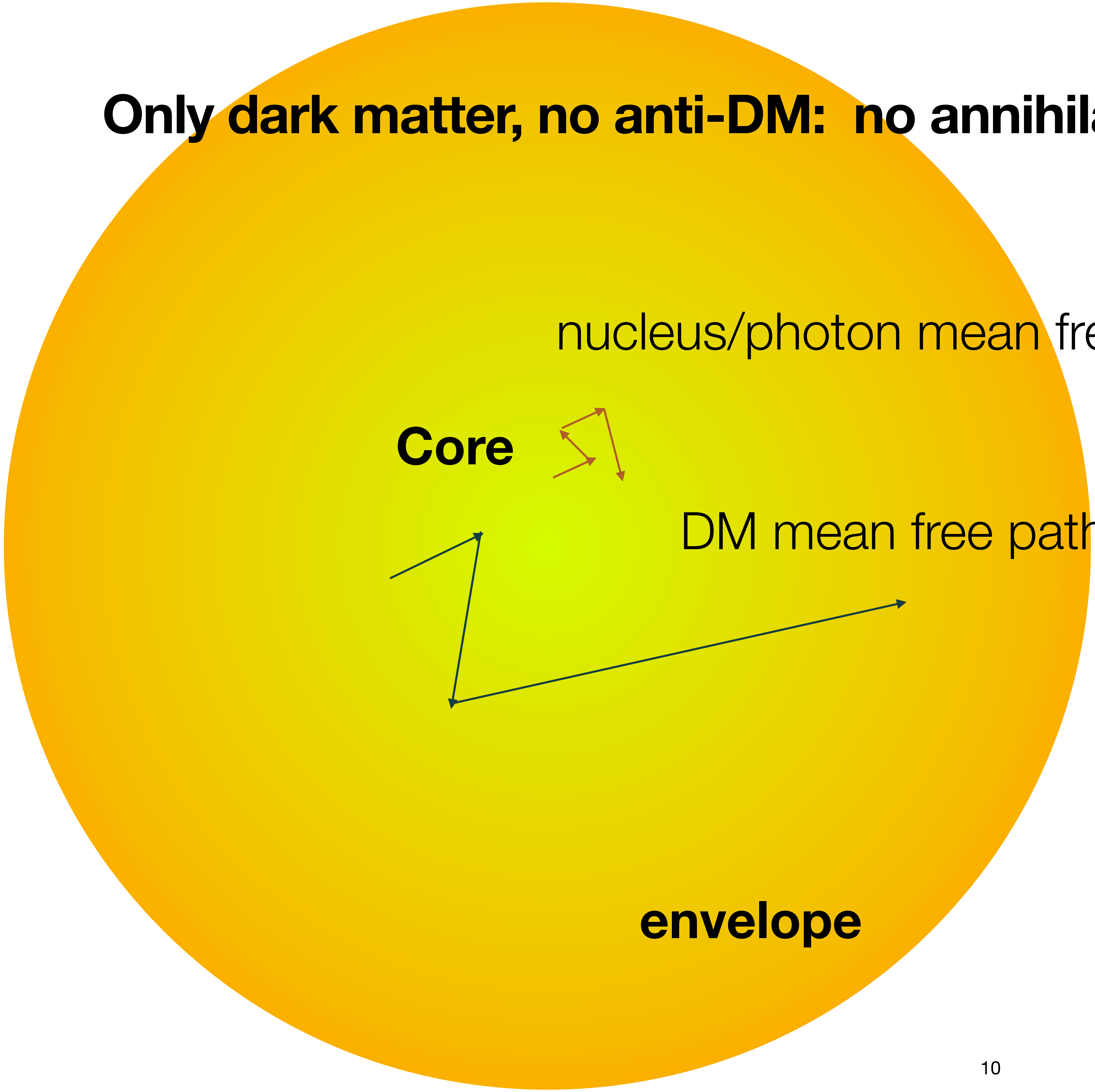
More extreme environments



Lopes & Lopes 2107.13885

With a **lot** of annihilating dark matter in the cores of stars, can provide enough extra heat to prematurely **ignite helium** burning in red giant stars, lowering the **tip of the red giant branch** (TRGB)

Only dark matter, no anti-DM: no annihilation; DM accumulates



$\sigma \simeq \sigma_T$

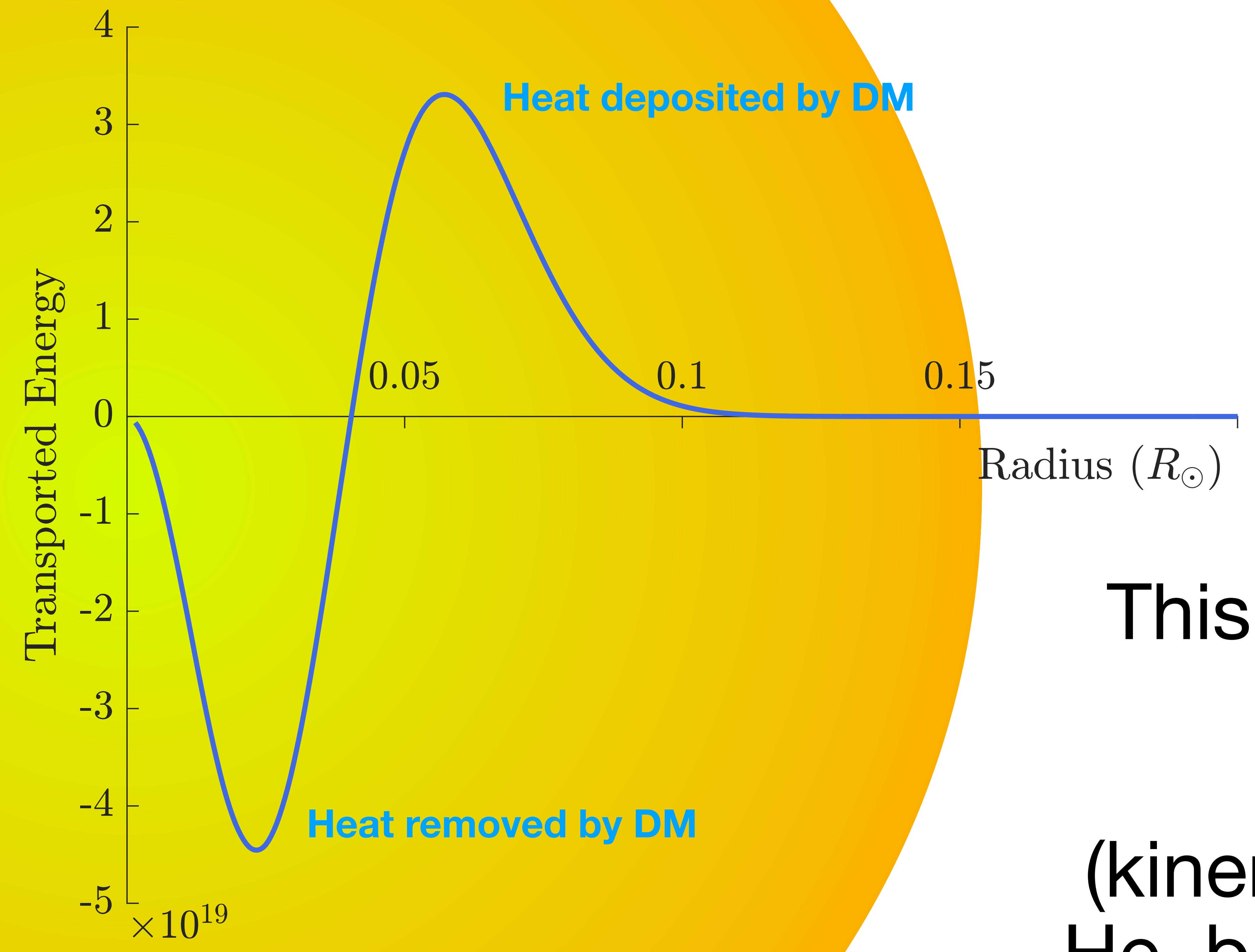
nucleus/photon mean free path $\lambda_{\rm nuc} \ll r_{\rm core}$

DM mean free path $\lambda_\chi \gg \lambda_{\rm nuc}$

$\sigma \ll \sigma_T$

Heat can be transported, changing the stellar temperature, density and pressure profiles

Heat transport by dark matter



This works best for dark matter $\sim 4-20$ GeV

(kinematically matched with H, He, but heavy enough not to evaporate)

Observable?

Change in radial heat transport

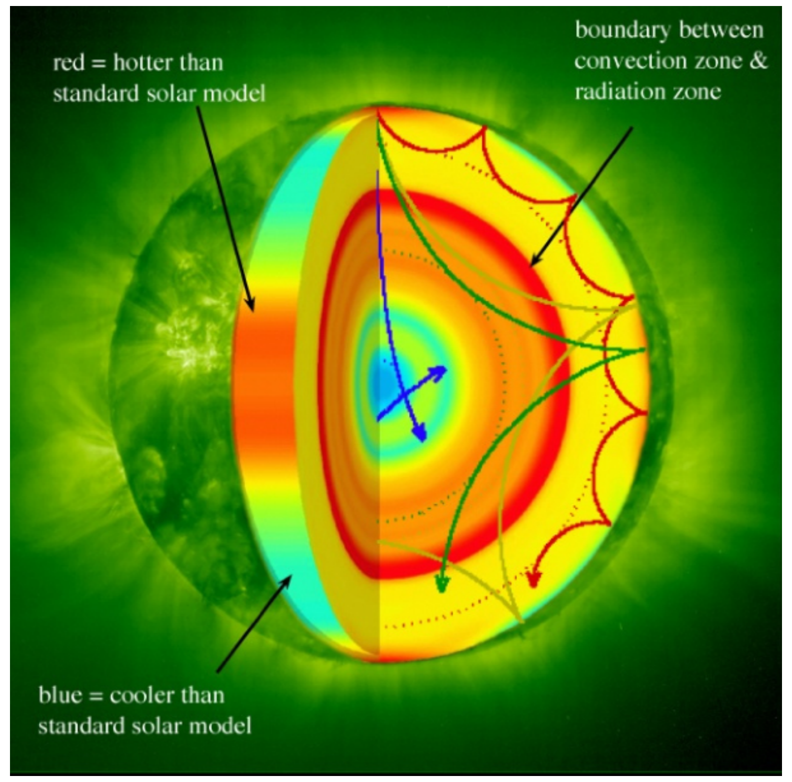
↓

Change in temperature profile

→ Small changes in pp fusion chain: reduction in ^{8}B and ^{7}Be **neutrino fluxes**

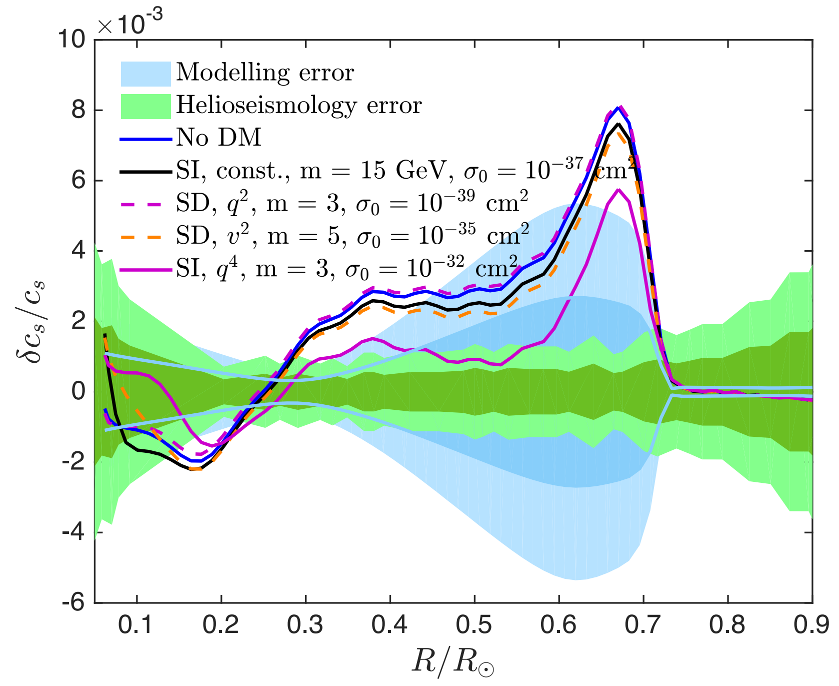
(these are the “regular” neutrinos from *pp* fusion, not annihilation)

→ Change in **pressure and density:** sound speed, Convective zone boundary



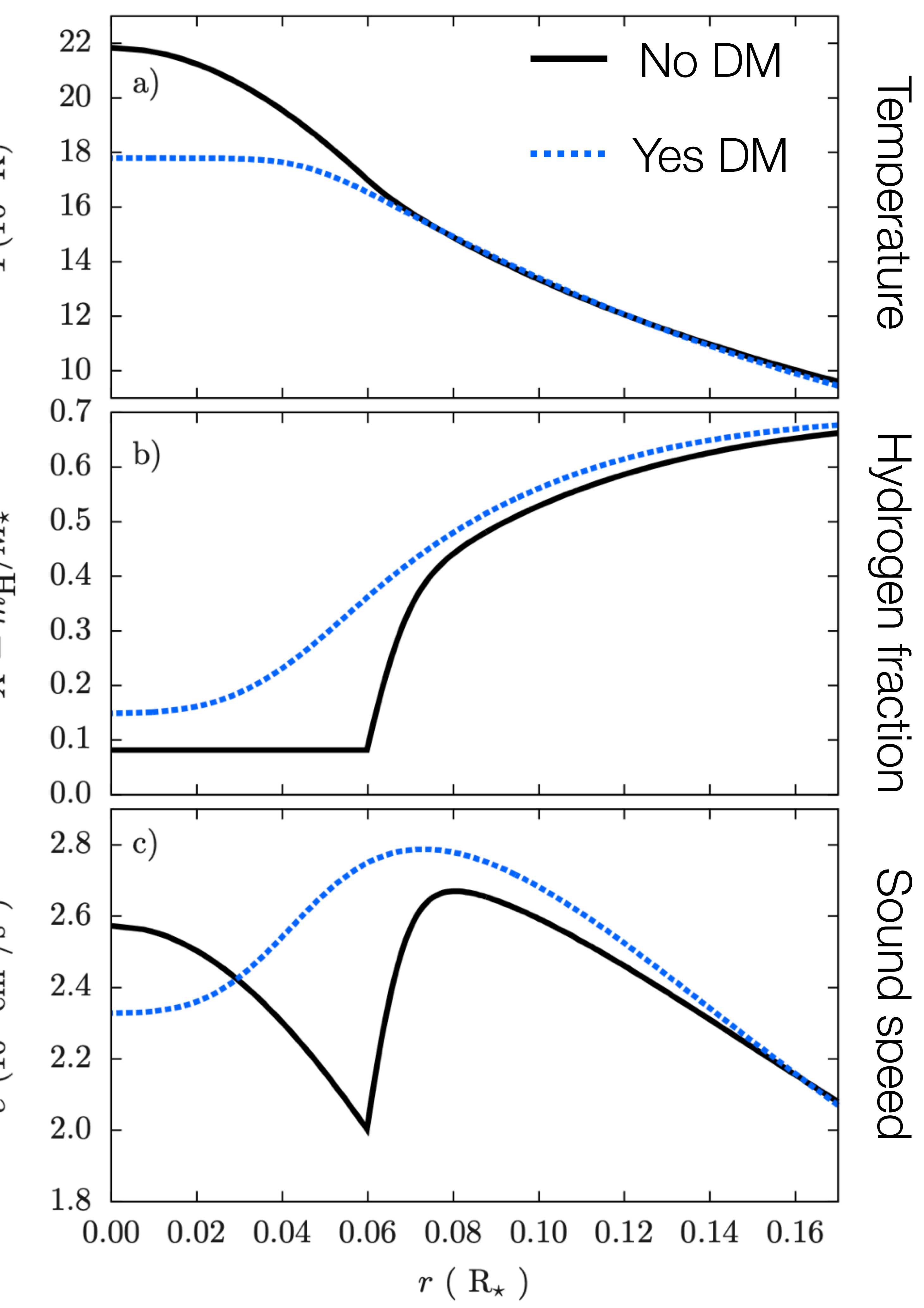
astero /helioseismology

Possible solution to solar composition problem? See ACV+ + 1605.06502

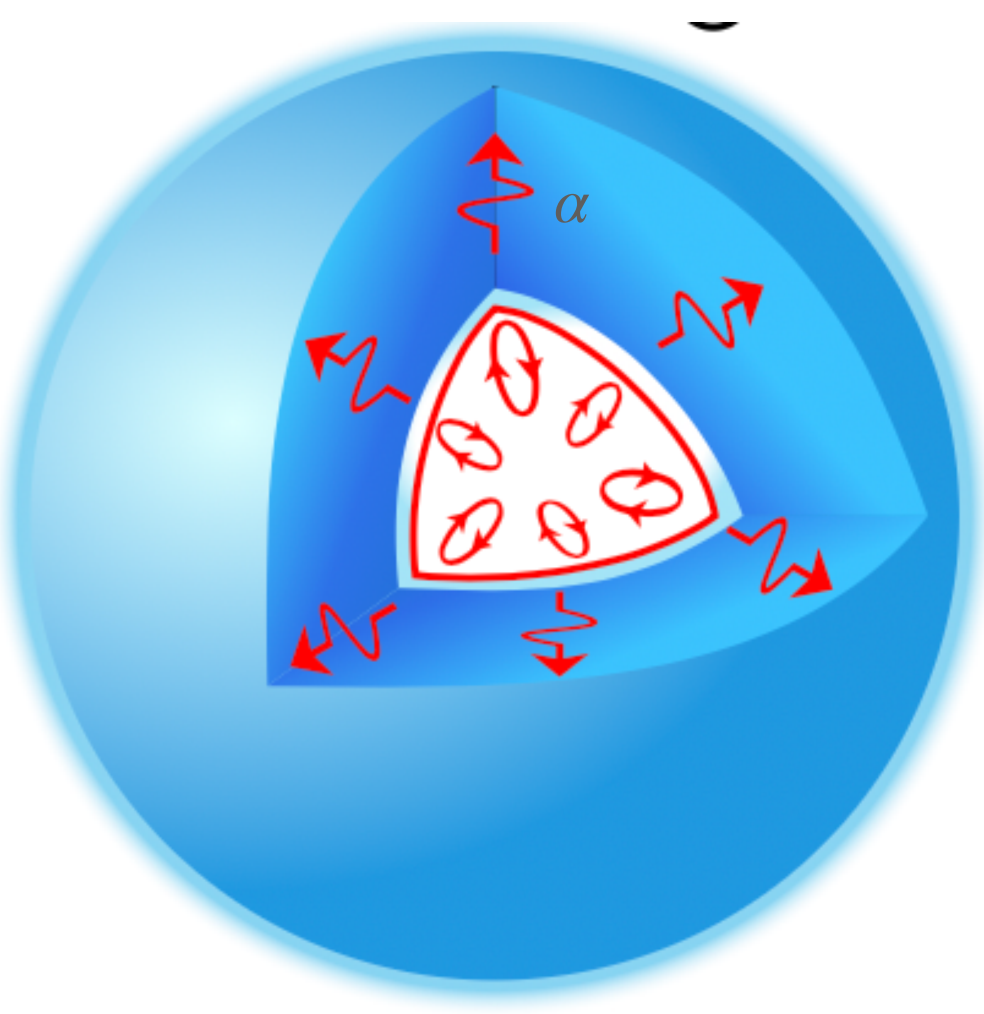


Dark matter in other stars

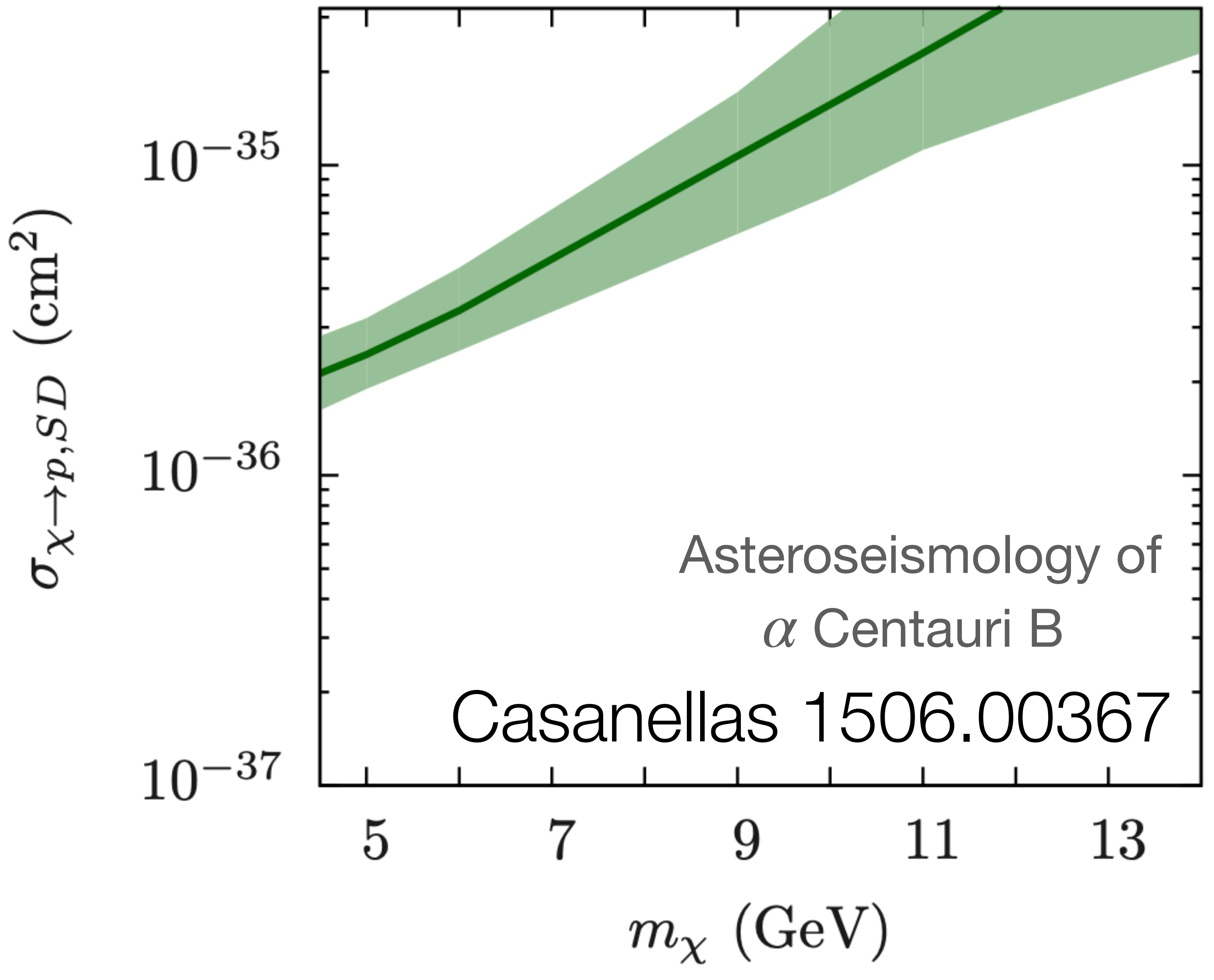
Casanellas et al 1505.01362



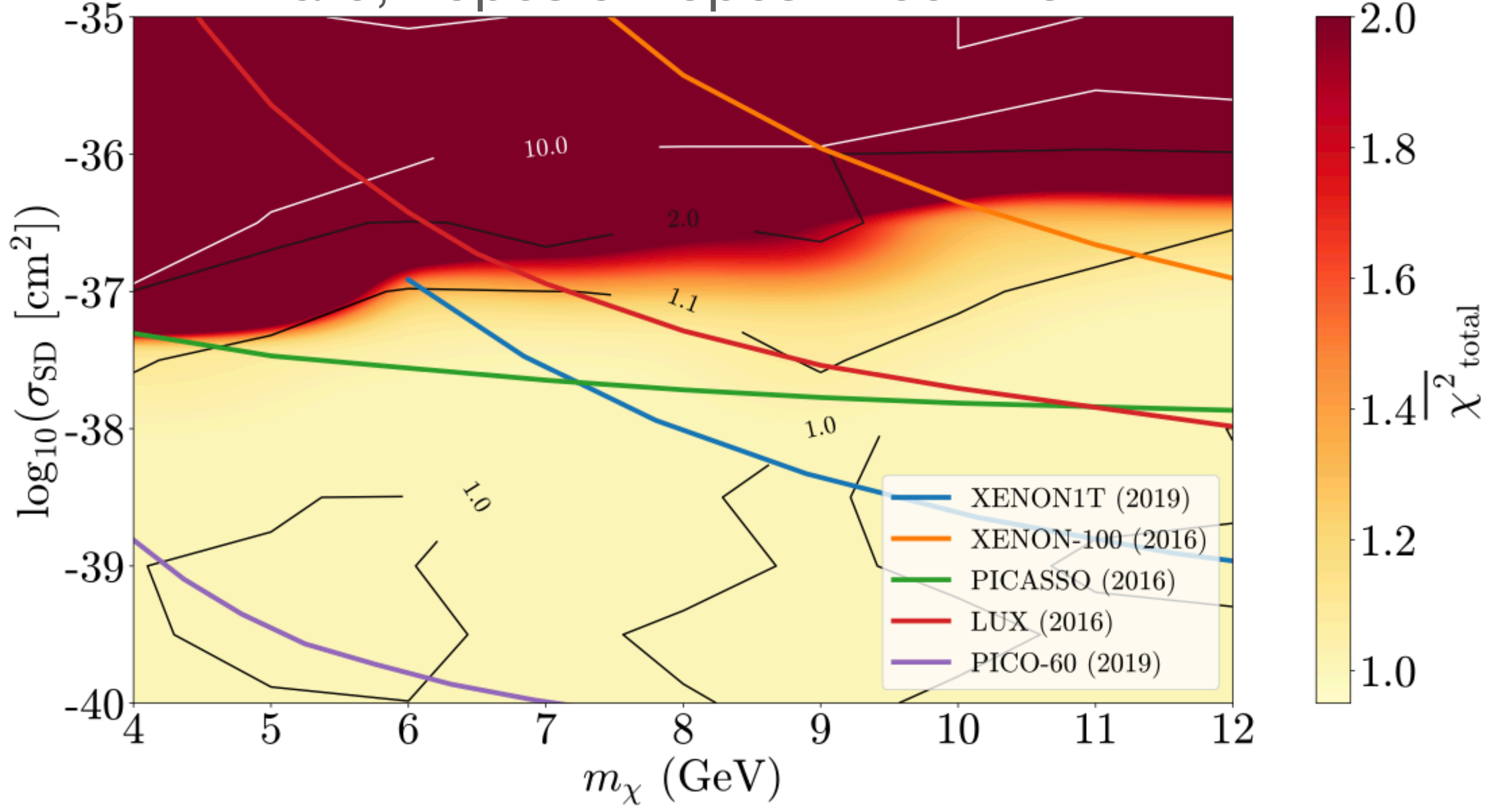
Nearby stars $\gtrsim$ 1.3 $M_\odot$:
Convective cores form in stars where the **temperature gradient** is too large to maintain hydrostatic equilibrium



DM can erase these cores, affecting **asteroseismology**



Rato, Lopes & Lopes 2109.12671

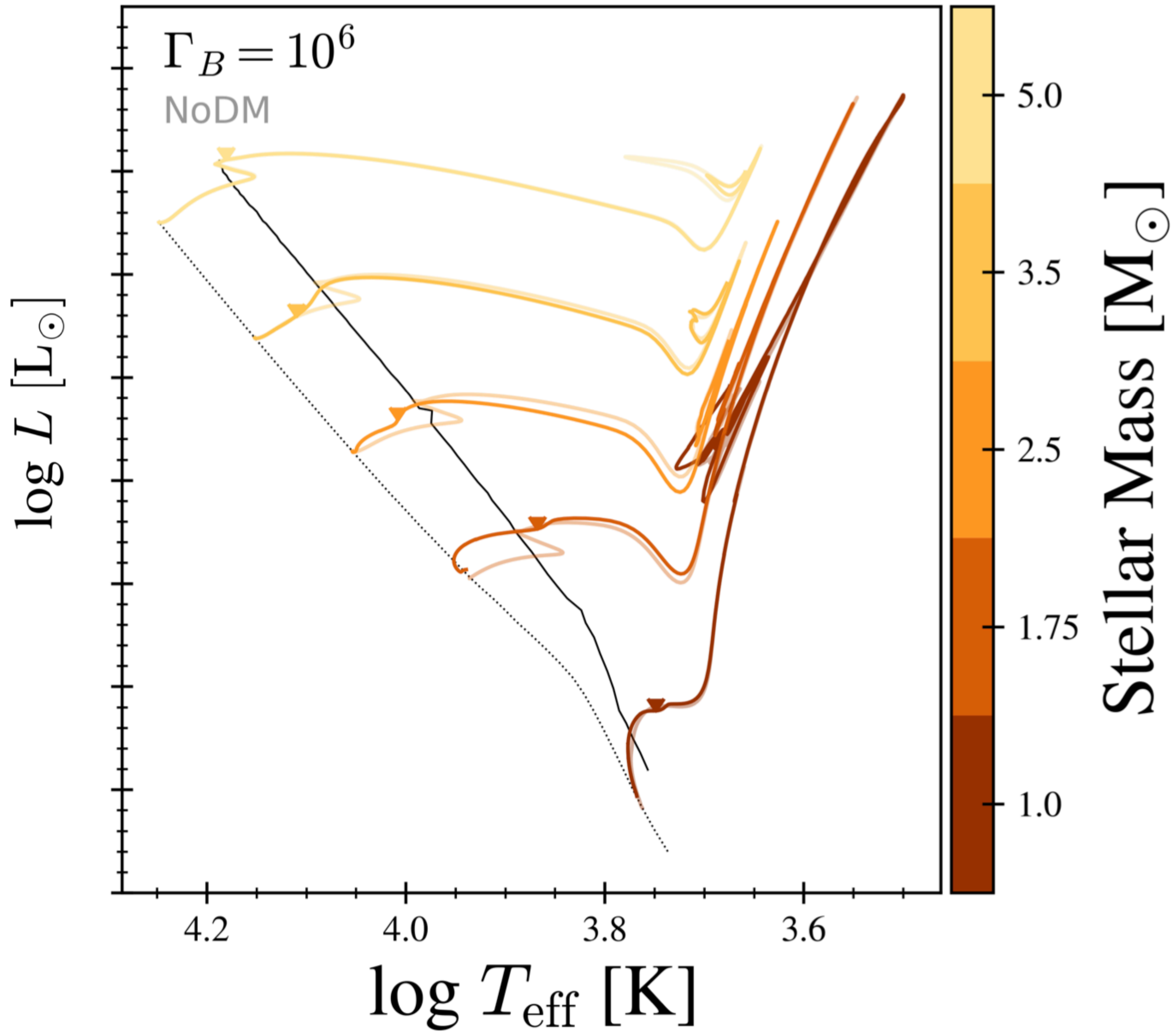


"Limit" from asteroseismology of a subgiant star

The Effects of Asymmetric Dark Matter on Stellar Evolution I: Spin-Dependent Scattering 2010.04184

Troy J. Raen,[1*], Héctor Martínez-Rodríguez[1], Travis J. Hurst[2], Andrew R. Zentner[1], and Carles Badenes[1], and Rachel Tao[3]

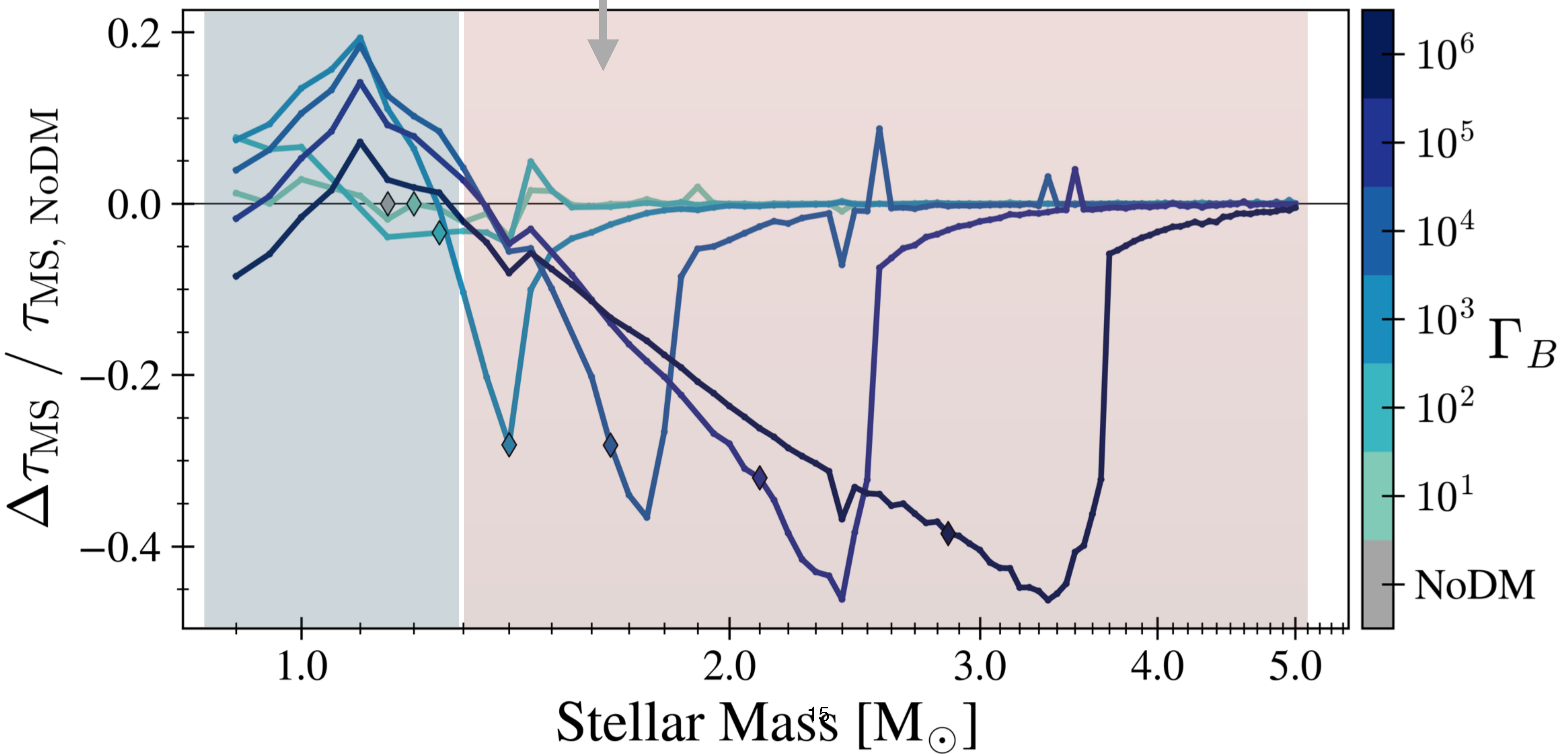
Large amounts of
DM: change trajectory on
HR diagram
erasure of convective
'hook' (because no
convective cores)



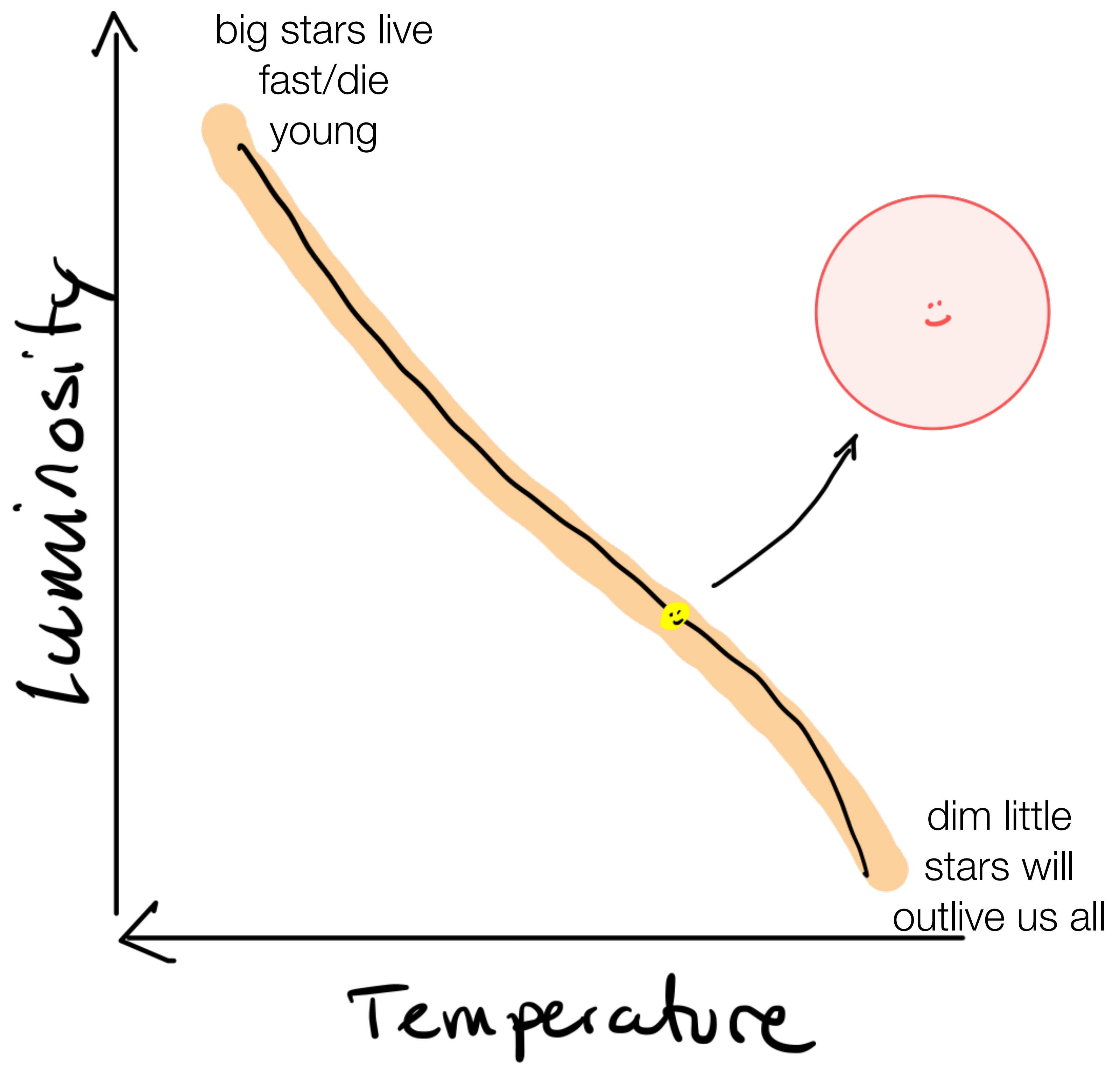
Raen et al 2010.04184: Main sequence lifetime

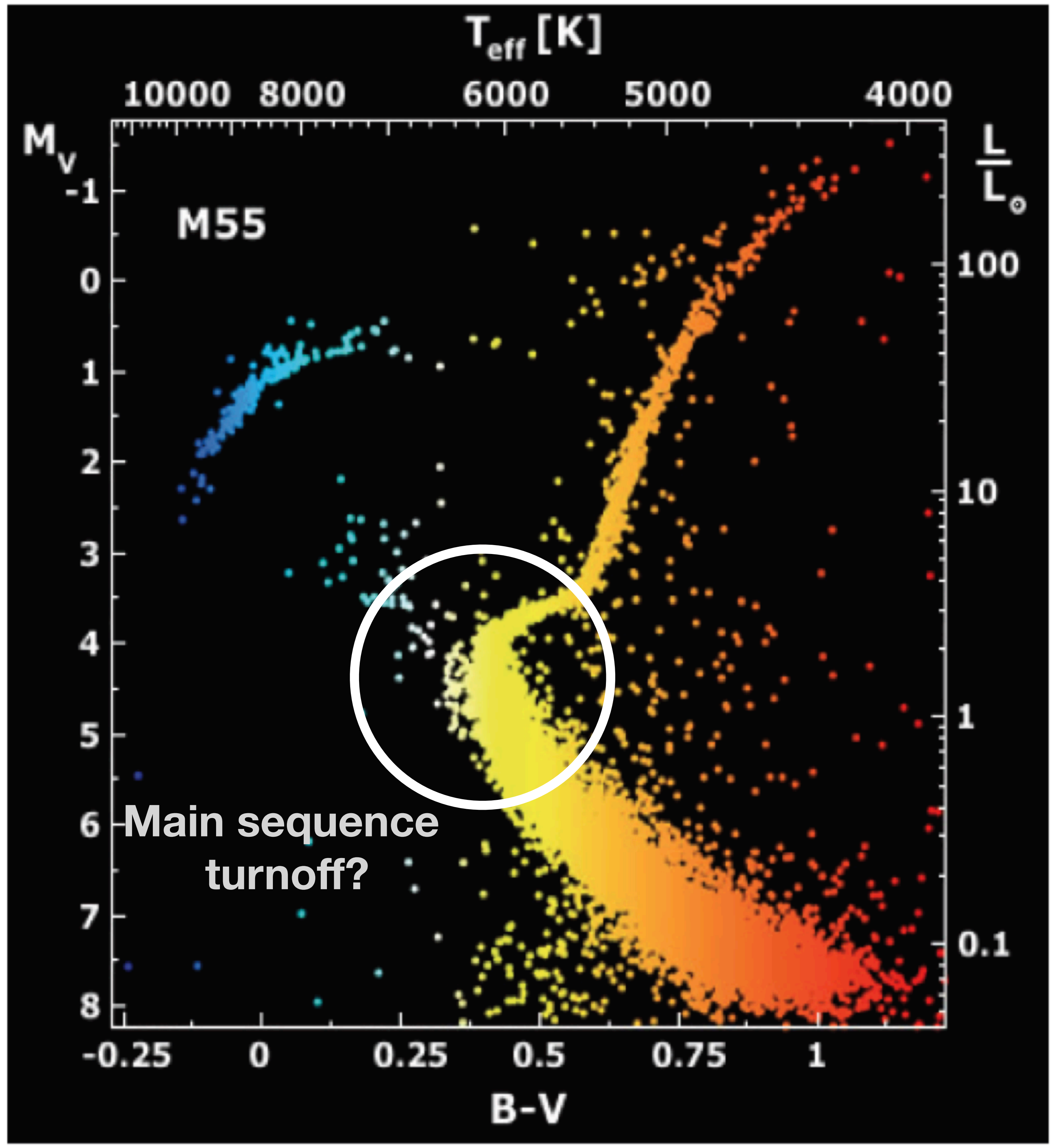
Low mass stars: larger core — more available H to fuse, longer lifetime

High mass stars: suppression of convective core — no mixing = less available fuel. Shorter lifetime



Main sequence lifetime?





Look at homogeneous populations of stars & compare with predictions? (work in progress)

But all of this is wrong

Actually the conclusions are likely to be qualitatively correct, but bear with me.

Heat conduction in stars

Boltzmann equation $DF(\mathbf{v}, \mathbf{r}, t) = \frac{1}{\ell_\chi} CF(\mathbf{v}, \mathbf{r}, t)$

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla_{\vec{r}} - (\nabla \phi(r))\hat{r} \cdot \nabla_v\right) F(\vec{v}, \vec{r}, t) = \frac{1}{\ell_\chi} \int d^3u \int d\Omega \sigma(\hat{\Omega}) |\vec{v} - \vec{u}| \left[F(\vec{v}', \vec{r}, t) F_N(\vec{u}', \vec{r}) - F(\vec{v}, \vec{r}, t) F_N(\vec{u}, \vec{r})\right]$$

= 6-dimensional integro-differential equation

Must be solved consistently **at every time step** in stellar evolution

Banks, Ansari, Scott, ACV 2111.06895

Heat conduction in stars

Boltzmann equation $$DF(\mathbf{v}, \mathbf{r}, t) = \frac{1}{\ell_\chi} CF(\mathbf{v}, \mathbf{r}, t)$$

How to solve:

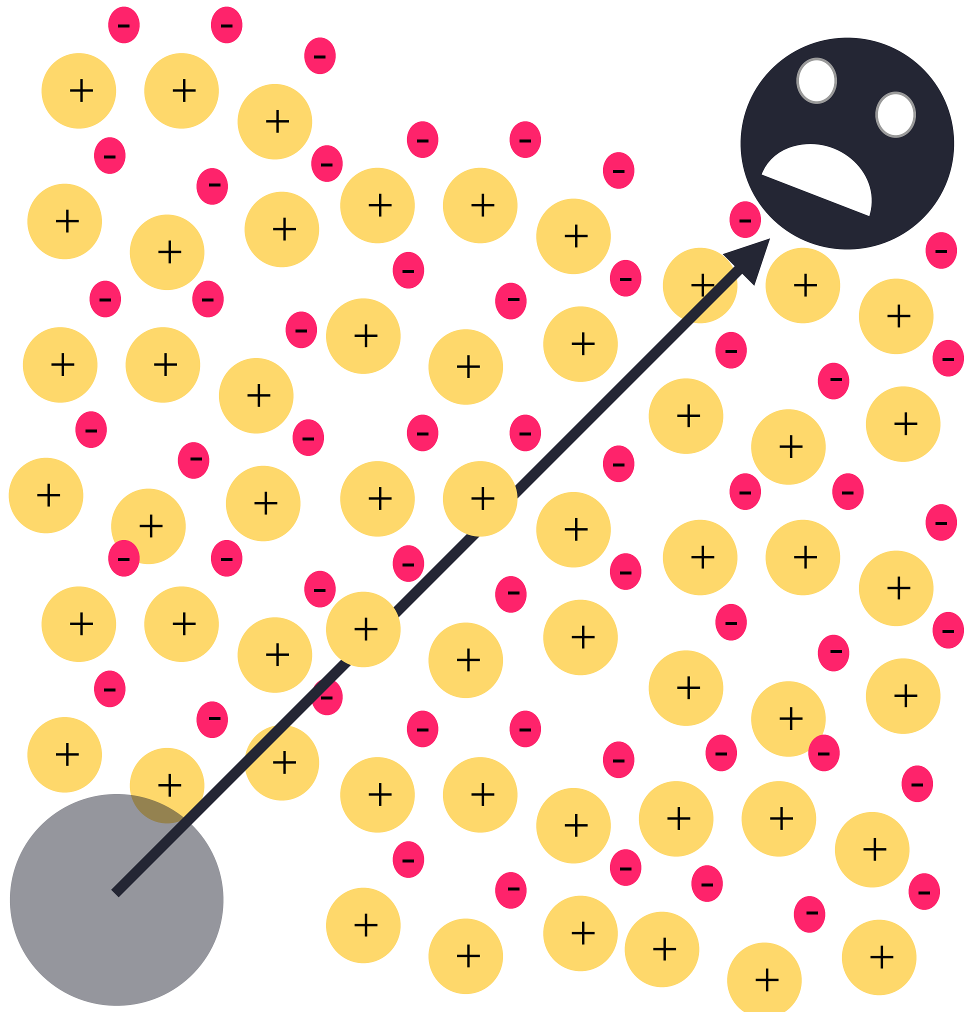
-Solve in the limit of **very large**, or **very small** cross section

Spergel & Press 1985, Gould & Raffelt 1990

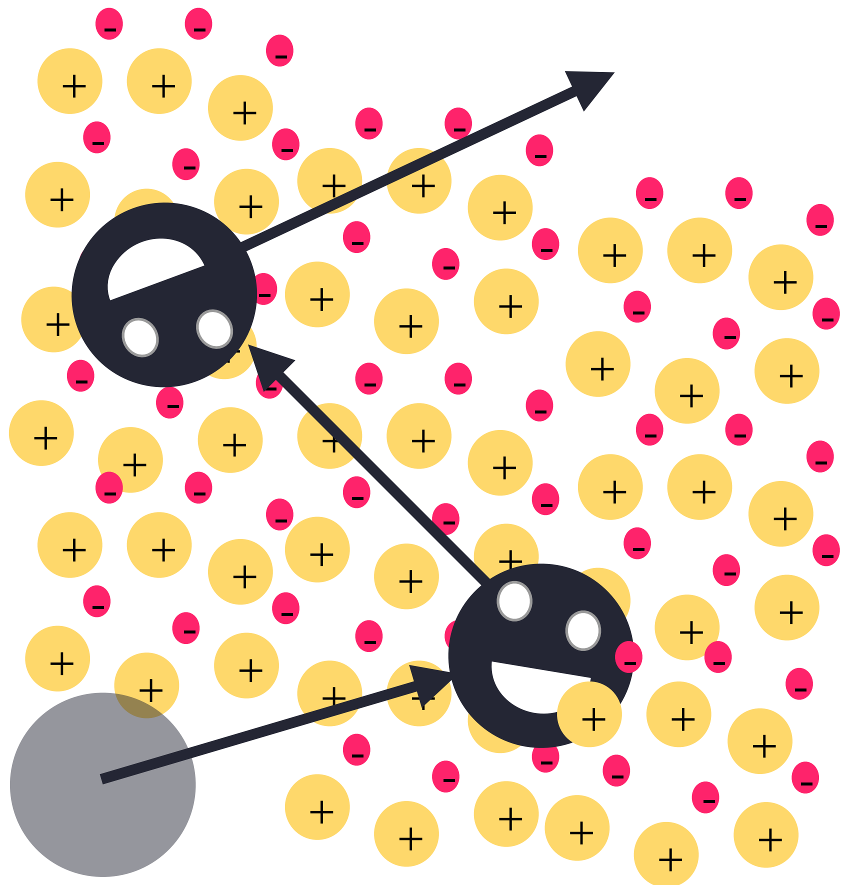
-Check your answer with a **Monte Carlo** (Gould & Raffelt, 1990)

Heat conduction in stars

Interactions too weak



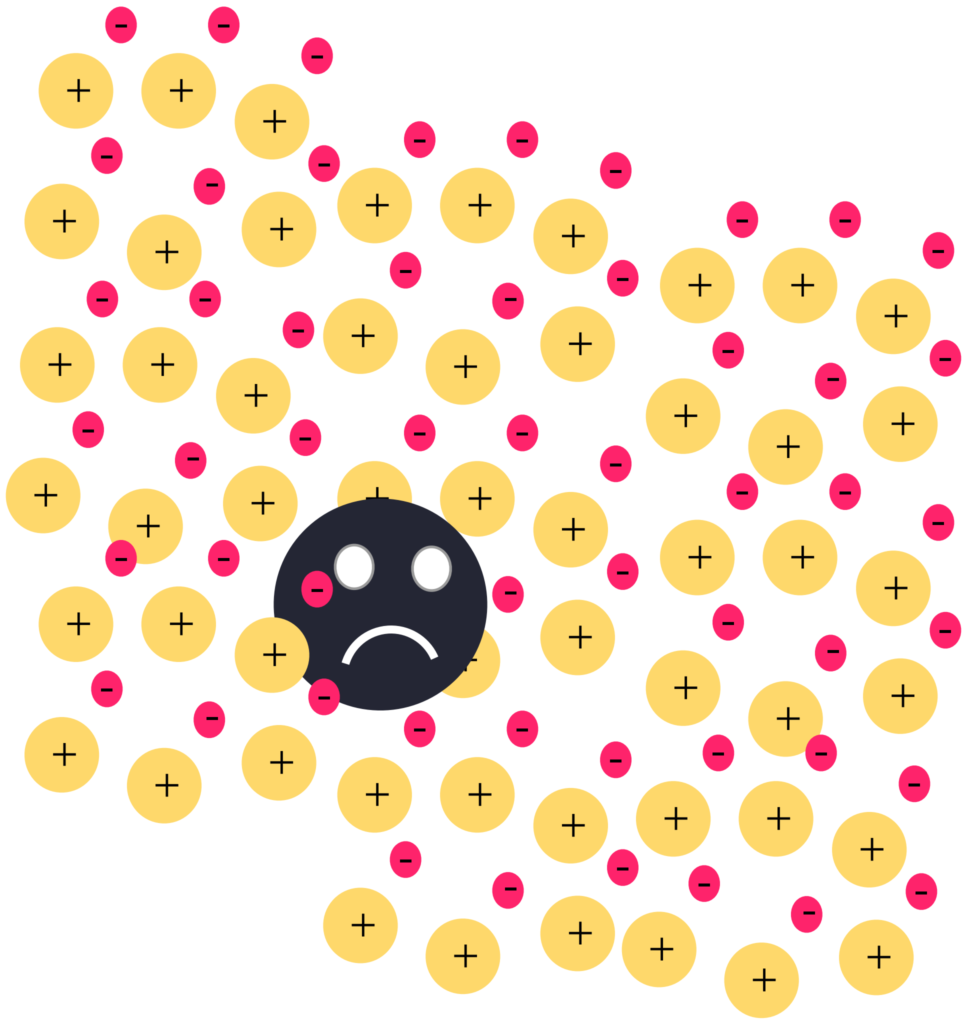
DM goes far but
cannot efficiently transfer momentum



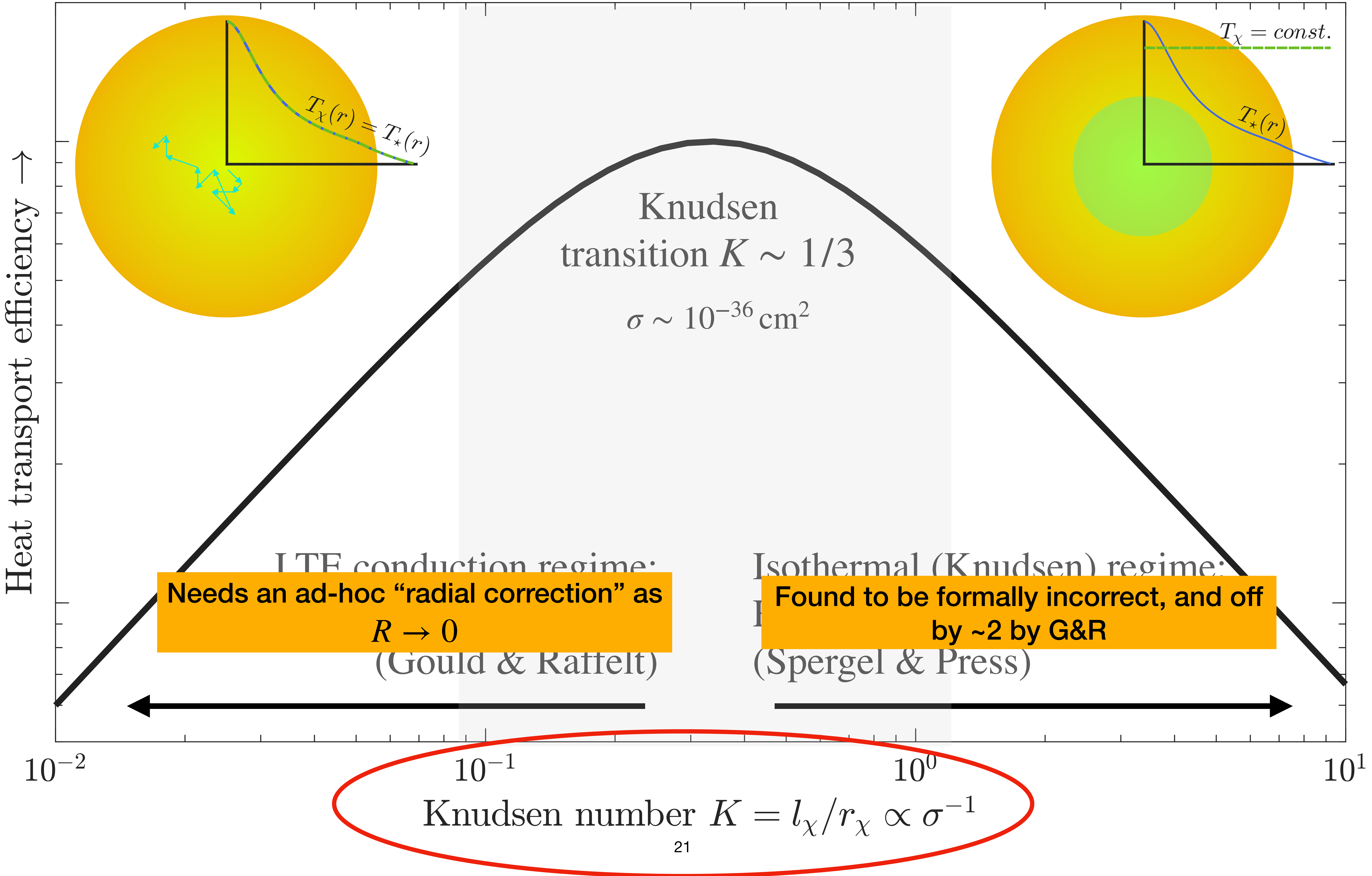
optimal heat transport:
“Knudsen Peak”

$\sigma_{\chi N} \sim$ **dark matter scale height**

Interactions too strong

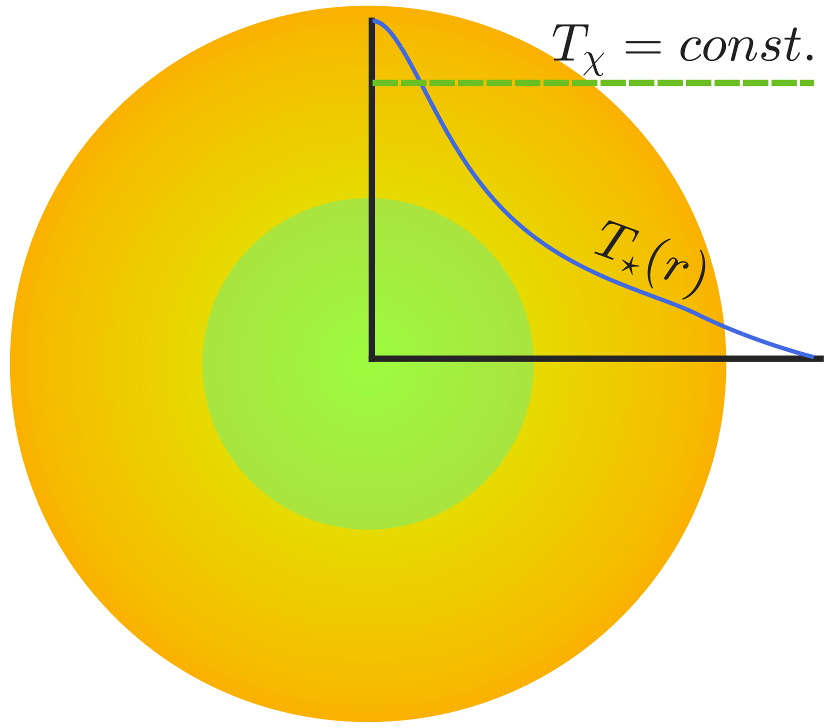


Efficient momentum transfer but
DM is “stuck"



Heat transport efficiency →
$T_\chi(r) = T_\star(r)$
$T_\chi = const.$
$T_\star(r)$
Knudsen
transition $K \sim 1/3$
$\sigma \sim 10^{-36}\,\mathrm{cm}^2$
LTE conduction regime:
Needs an ad-hoc “radial correction” as $R \to 0$
(Gould & Raffelt)
Isothermal (Knudsen) regime:
Found to be formally incorrect, and off by ~2 by G&R
(Spergel & Press)
10^{-2}
10^{-1}
10^{0}
10^{1}
Knudsen number $K = l_\chi / r_\chi \propto \sigma^{-1}$

Solution method 1: isothermal (Spergel & Press, 1984)



$$DF(\mathbf{v}, \mathbf{r}, t) \simeq 0 \quad \rightarrow F \sim \exp\left(-\frac{\frac{1}{2}mv^2 + m\phi(r)}{kT_\chi}\right)$$

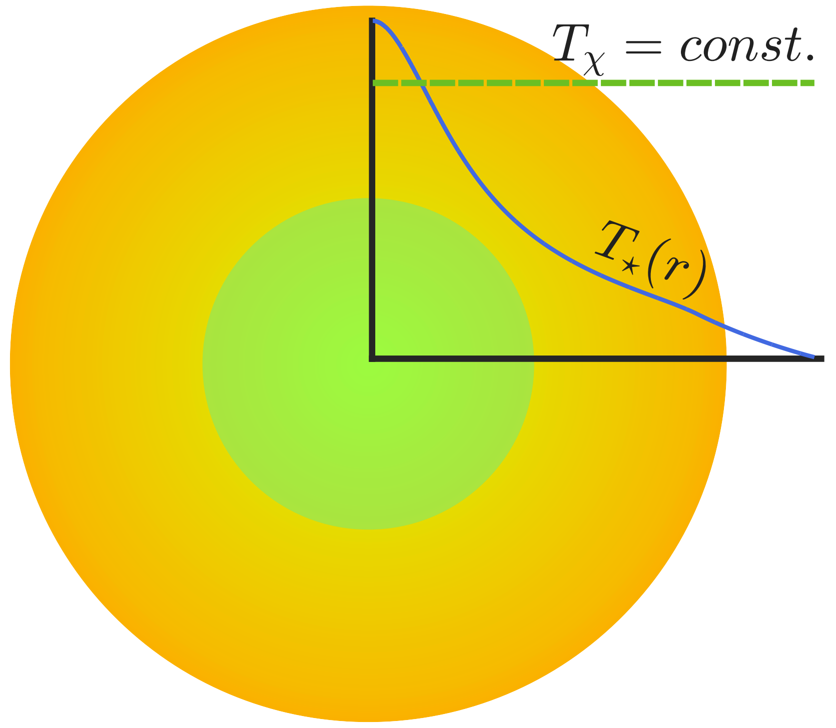
DM is at a single 'average' temperature T_χ

Conduction treated as contact between two weakly coupled heat baths

$$\epsilon \propto \sigma\big(T_\star(r) - T_\chi\big)$$

- Heat removed from star where $T_\star(r) > T_\chi$
- Heat deposited in star where $T_\star(r) < T_\chi$

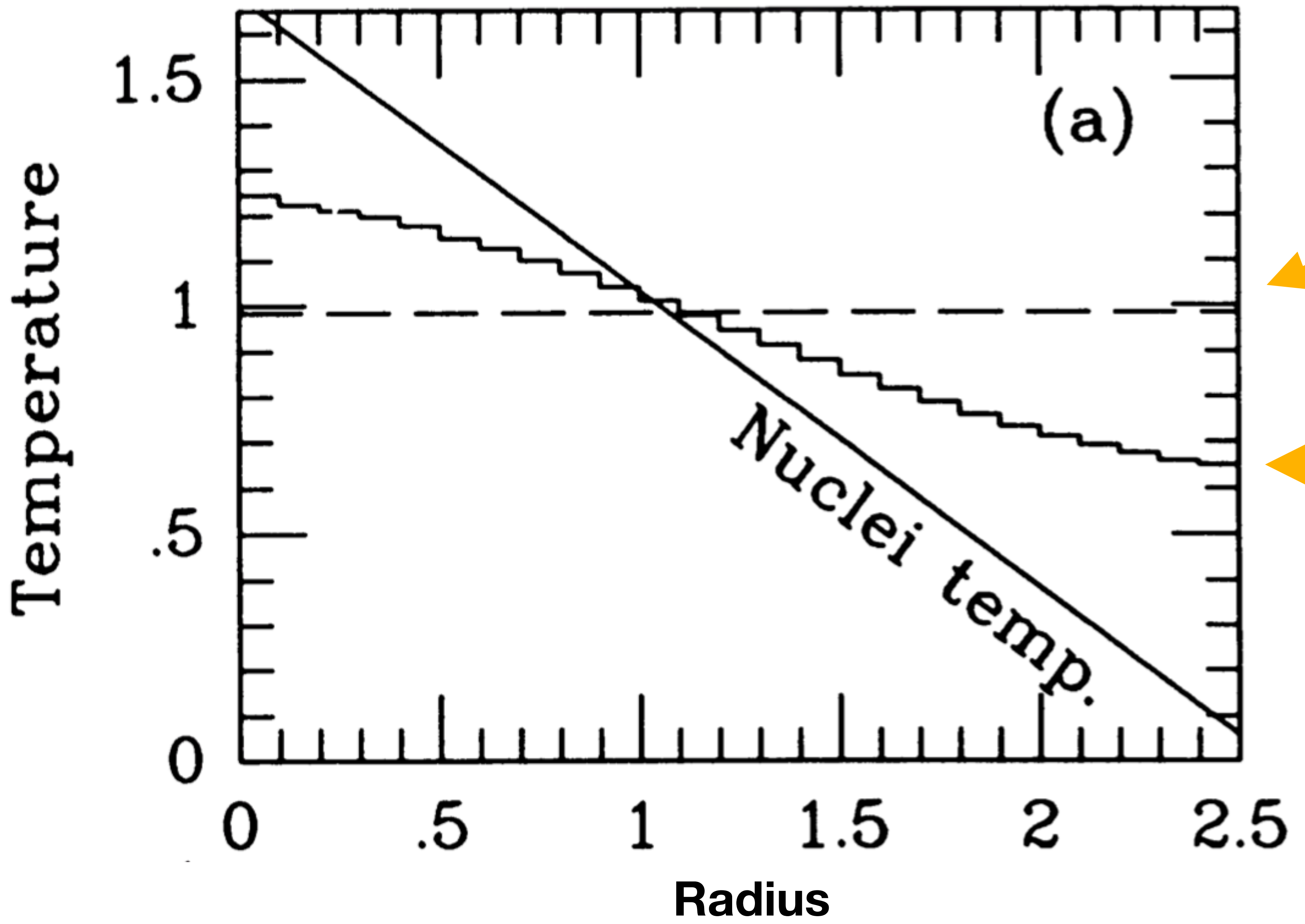
Solution method 1: isothermal (Spergel & Press, 1984)



$$\epsilon \propto \sigma\left(T_\star(r) - T_\chi\right)$$

This has been known to be formally incorrect since 1990, but is still most widely used because it is numerically stable

Gould & Raffelt 1990 Monte Carlo simulation

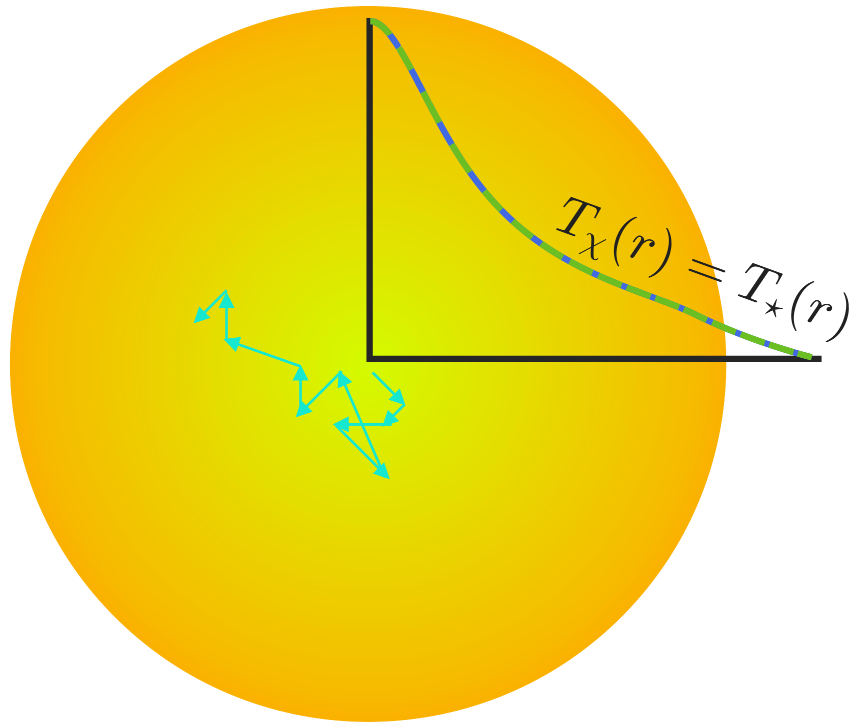


Isothermal assumption T_χ

Actual DM temperature

ΔT overestimated →heat transfer overestimated **by a factor of 2**

Solution method 2: corrected LTE (Gould & Raffelt, 1990)



If $\ell \ll r_\chi$, conduction is **local** $(T_\chi(r) \simeq T_\star(r))$

Expand $DF(\mathbf{v}, \mathbf{r}, t) = \dfrac{1}{\ell_\chi} CF(\mathbf{v}, \mathbf{r}, t)$ in a series in $\ell_\chi |\nabla \ln T_\star|$

Solve first order dipole (only care about radial part)

Distribution

$$n_{\chi,\mathrm{LTE}}(r) = n_\chi(0) \left[\frac{T(r)}{T(0)}\right]^{3/2} \exp\left[-\int_0^r dr' \frac{k_\mathrm{B}\alpha(r')\frac{dT(r')}{dr'} + m_\chi \frac{d\phi(r')}{dr'}}{k_\mathrm{B}T(r')}\right]$$

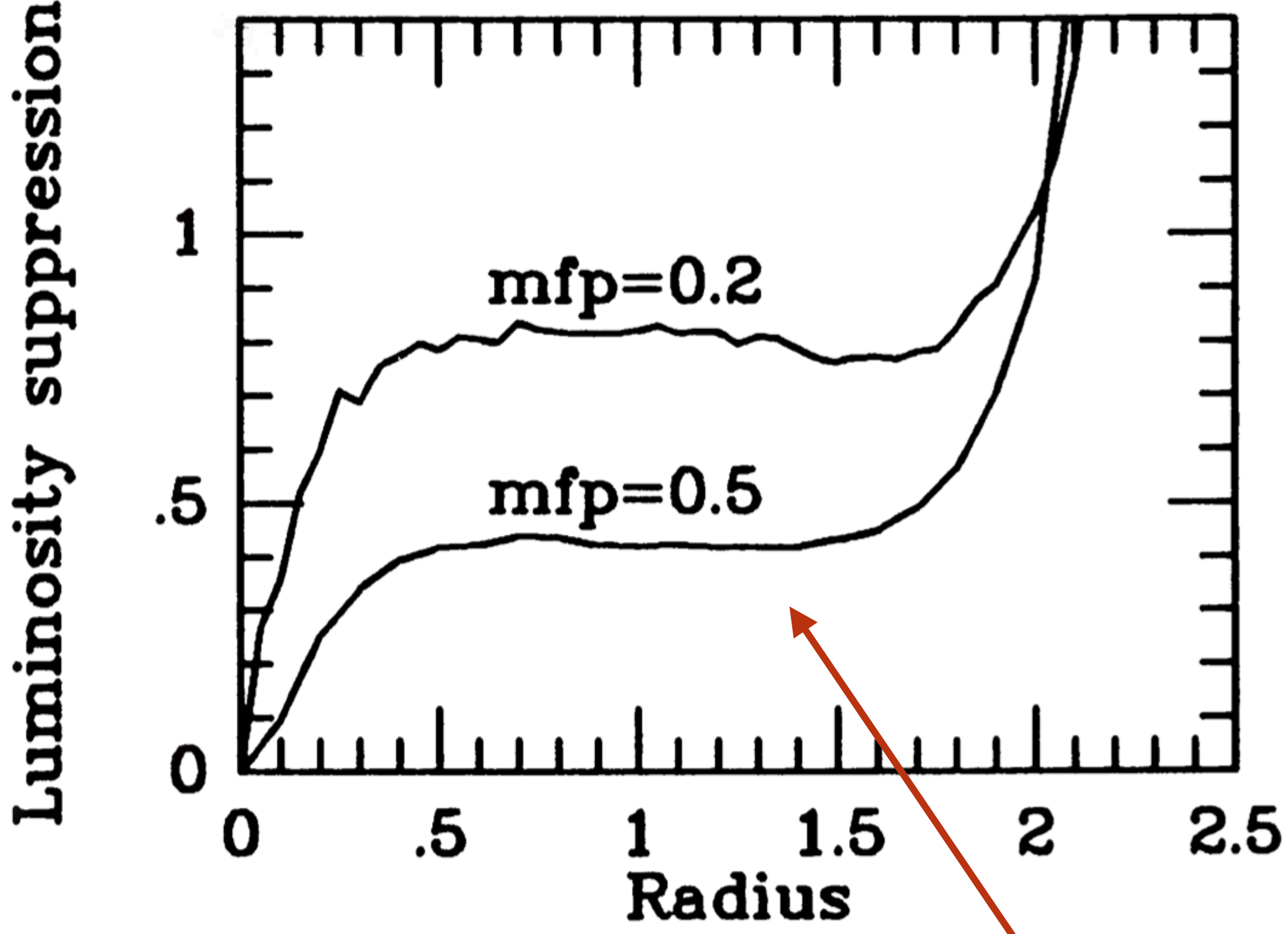
Luminosity

$$L_{\chi,\mathrm{LTE}}(r) = 4\pi r^2 \kappa(r) n_\chi(r) l_\chi(r) \left[\frac{k_\mathrm{B}T(r)}{m_\chi}\right]^{1/2} k_\mathrm{B} \frac{dT(r)}{dr},$$

α and κ only depend on $\dfrac{m_{\text{Dark matter}}}{m_{Nuclei}}$

Solution method 2: corrected LTE (Gould & Raffelt)

Gould & Raffelt 1990 Monte Carlo simulation



Two corrections still needed:

- **Knudsen suppression:** condition $\ell_\chi \ll |\nabla \ln T|^{-1}$ breaks down.
- **Radial suppression**: isotropy assumption breaks down at low radii

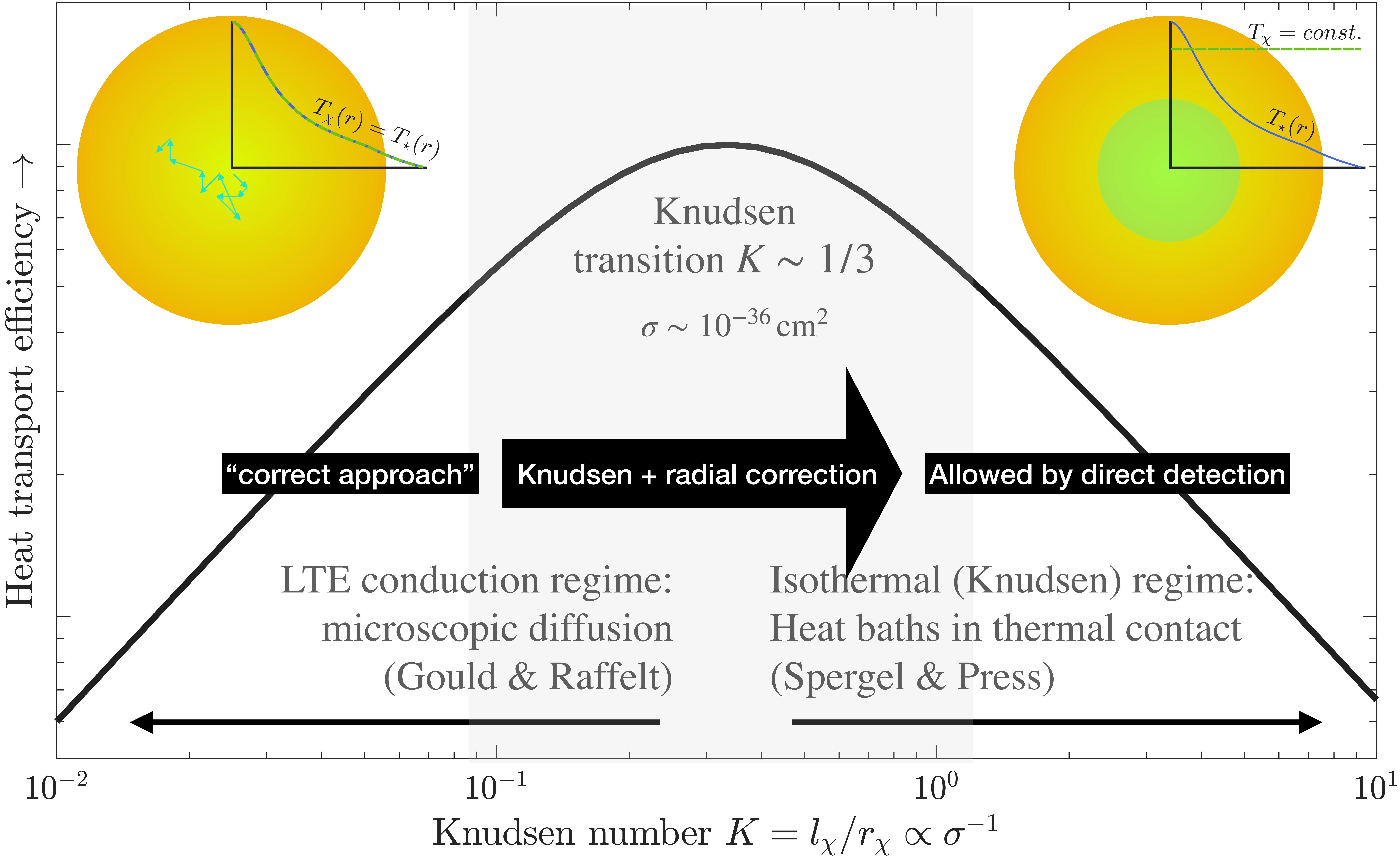
All “correct” results in the past 30 years use a fit to this graph to fix the LTE prediction

Additional technical issue: numerically unstable (reason method 1 still used)

Solution method 2: corrected LTE (Gould & Raffelt)

"Correct approach"

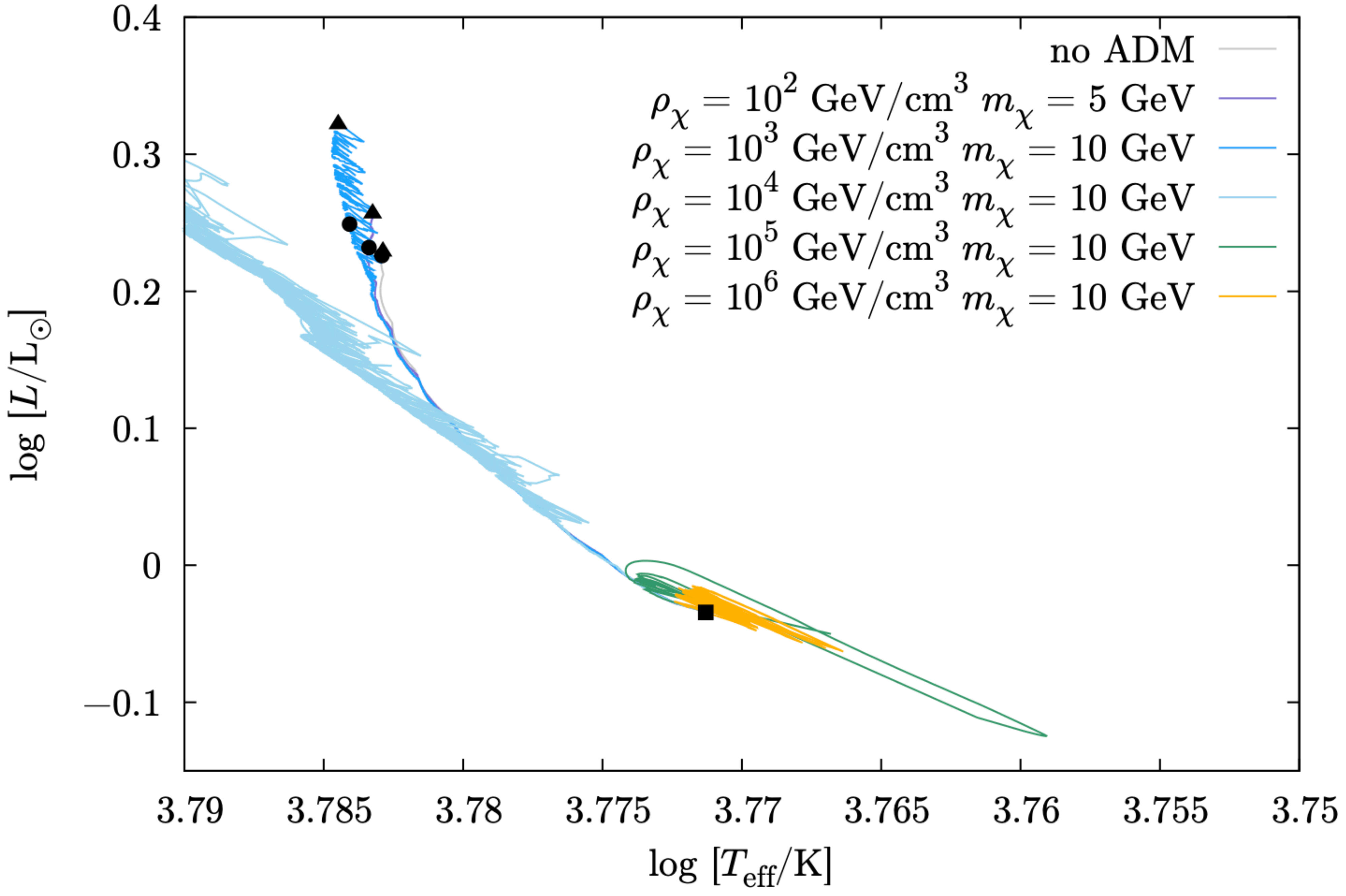
LTE (large cross section) approximation
Empirical correction so that it works at small cross sections



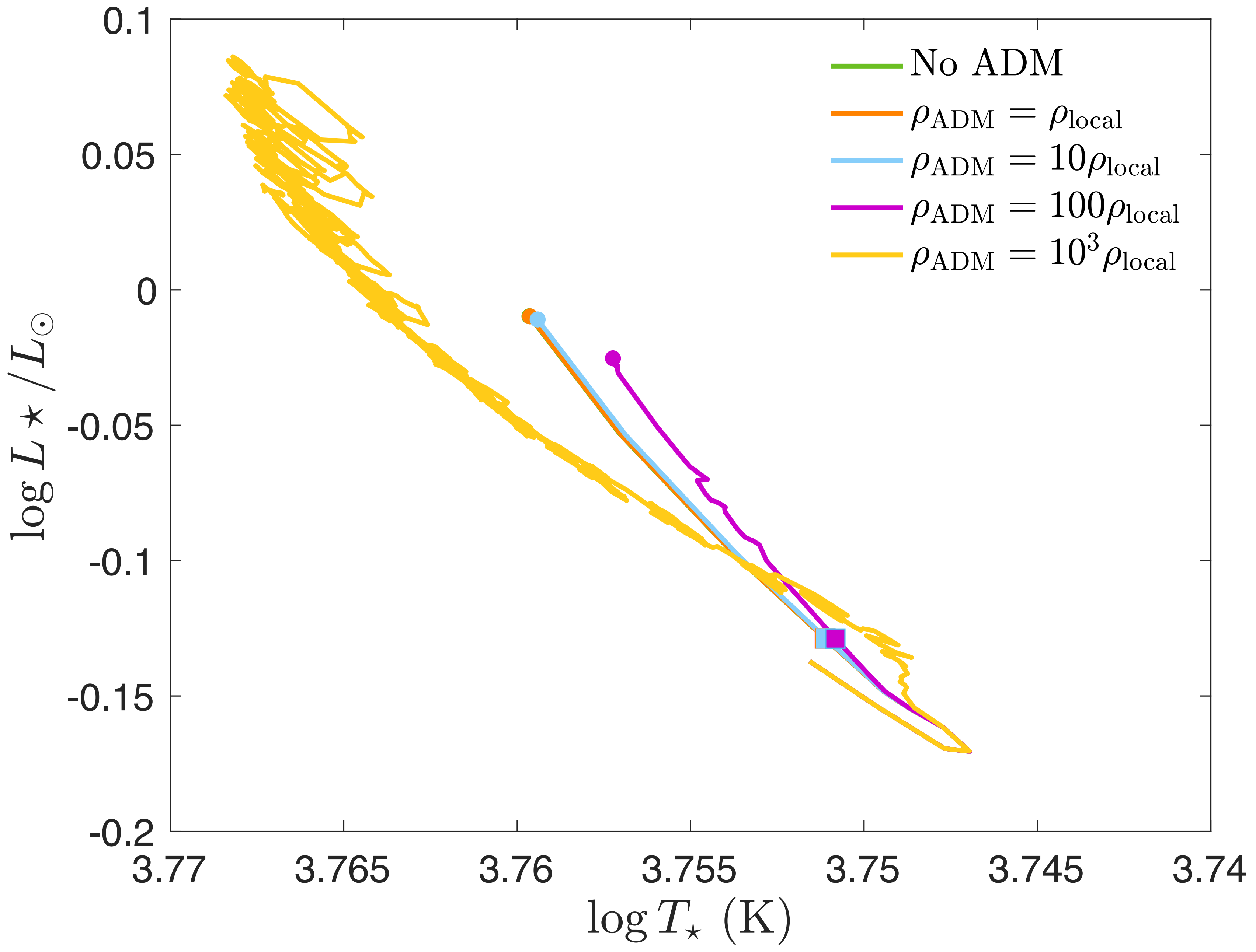
$T_\chi(r) = T_\star(r)$
$T_\chi = const.$
$T_\star(r)$
Knudsen transition $K \sim 1/3$
$\sigma \sim 10^{-36}\,\mathrm{cm}^2$
"correct approach"
Knudsen + radial correction
Allowed by direct detection
LTE conduction regime: microscopic diffusion (Gould & Raffelt)
Isothermal (Knudsen) regime: Heat baths in thermal contact (Spergel & Press)
Heat transport efficiency →
10^{-2}
10^{-1}
10^{0}
10^{1}
Knudsen number $K = l_\chi / r_\chi \propto \sigma^{-1}$

Another problem with the "correct" approach: numerical instabilities in stellar evolution codes

Iocco et al. (PRL) 1201.5387



ACV, Can. J. Mod. Art 2021



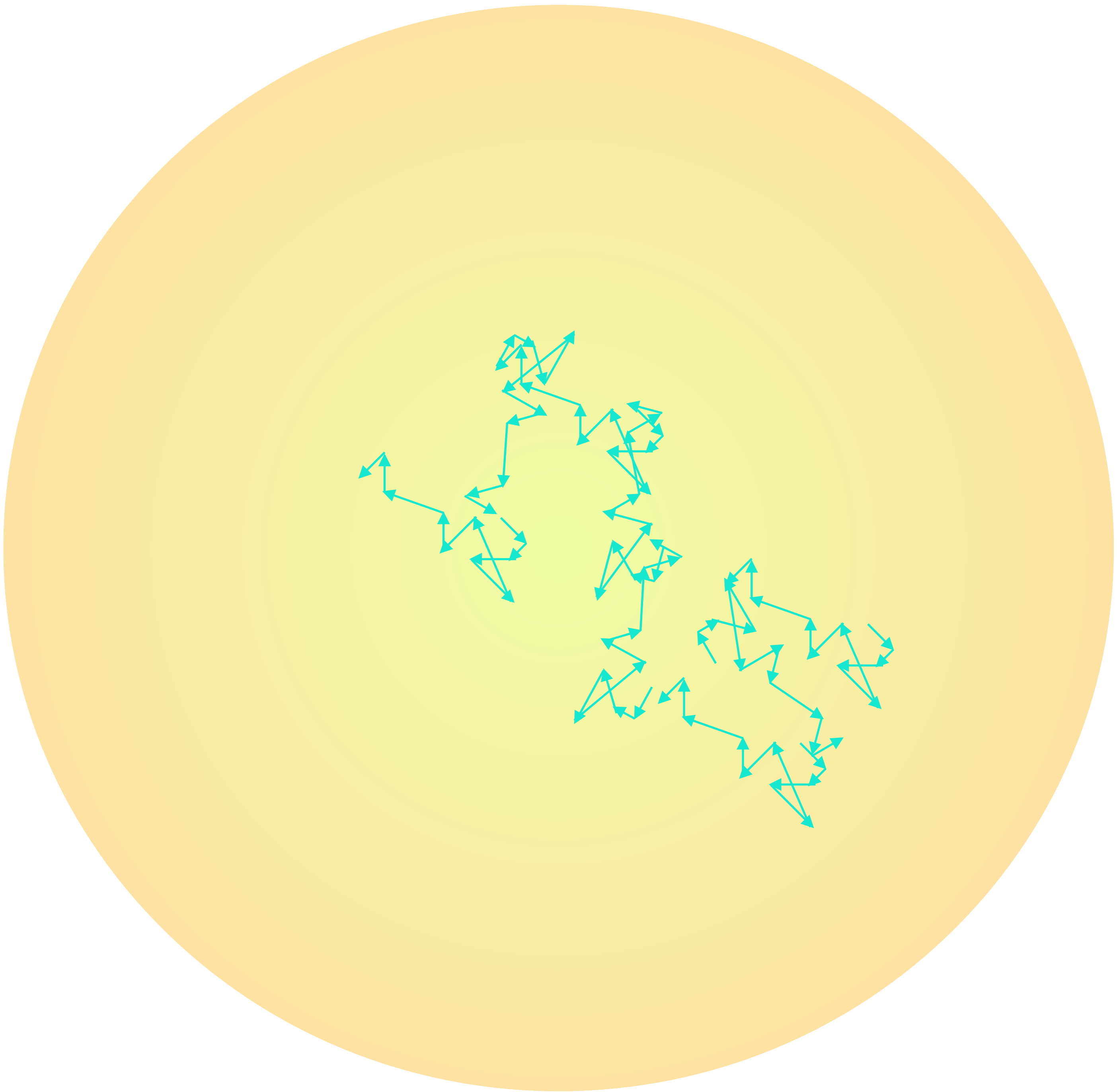
“Exact solution”: Monte Carlo

m_χ σ_0

$\sigma = const.$

$\sigma \propto v^{2n}$

$\sigma \propto q^{2n}$



1. Specify DM mass, cross section, interaction type

2. Initialize a particle in stellar environment (temperature gradient, density, gravitational potential)

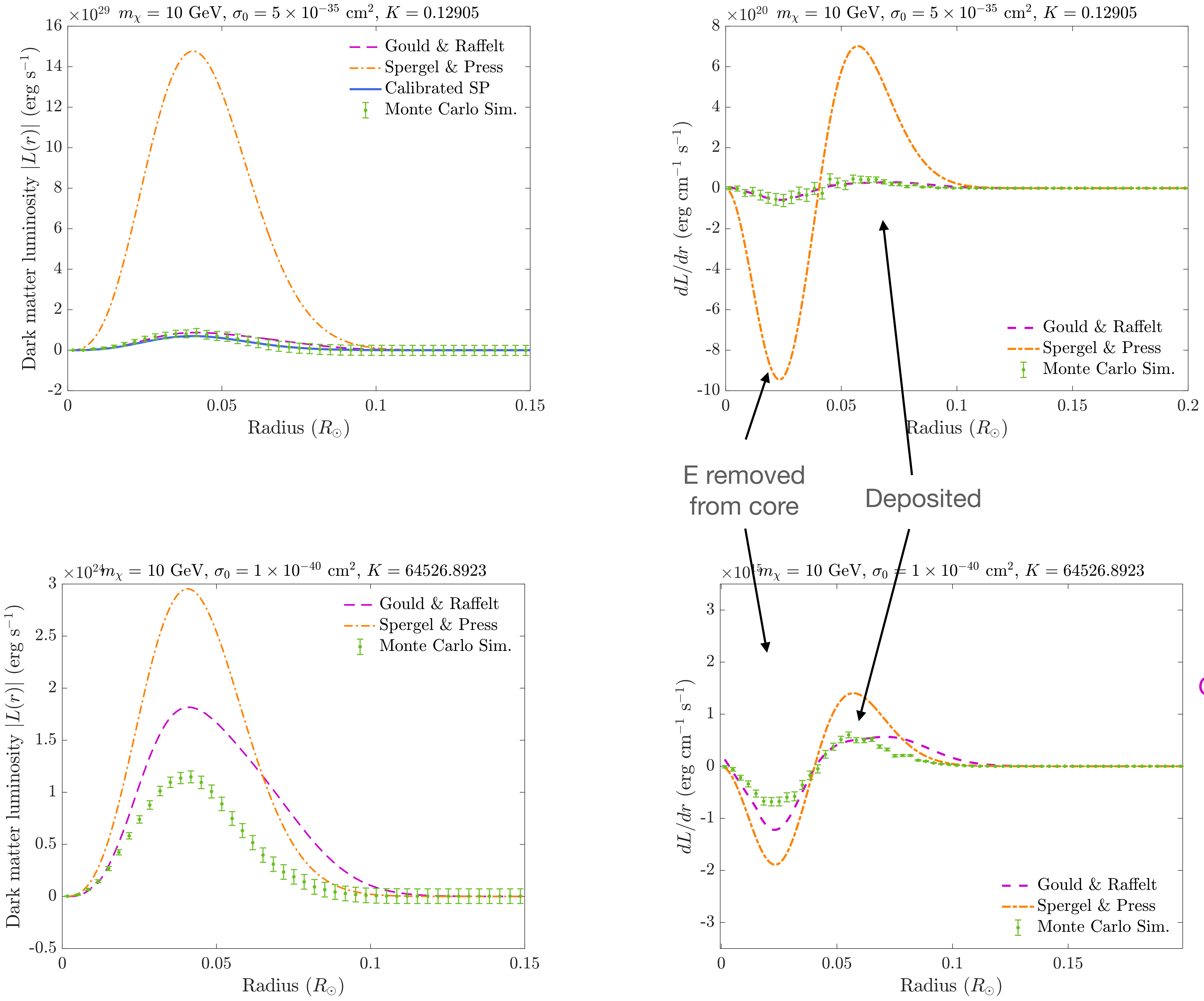
3. Let it evolve and scatter for N >> 1 iterations.

4. Ergodicity: phase space covered by particle ~ steady state distribution.

Luminosity | Transported energy

Large σ:
LTE regime

Small σ:
isothermal regime

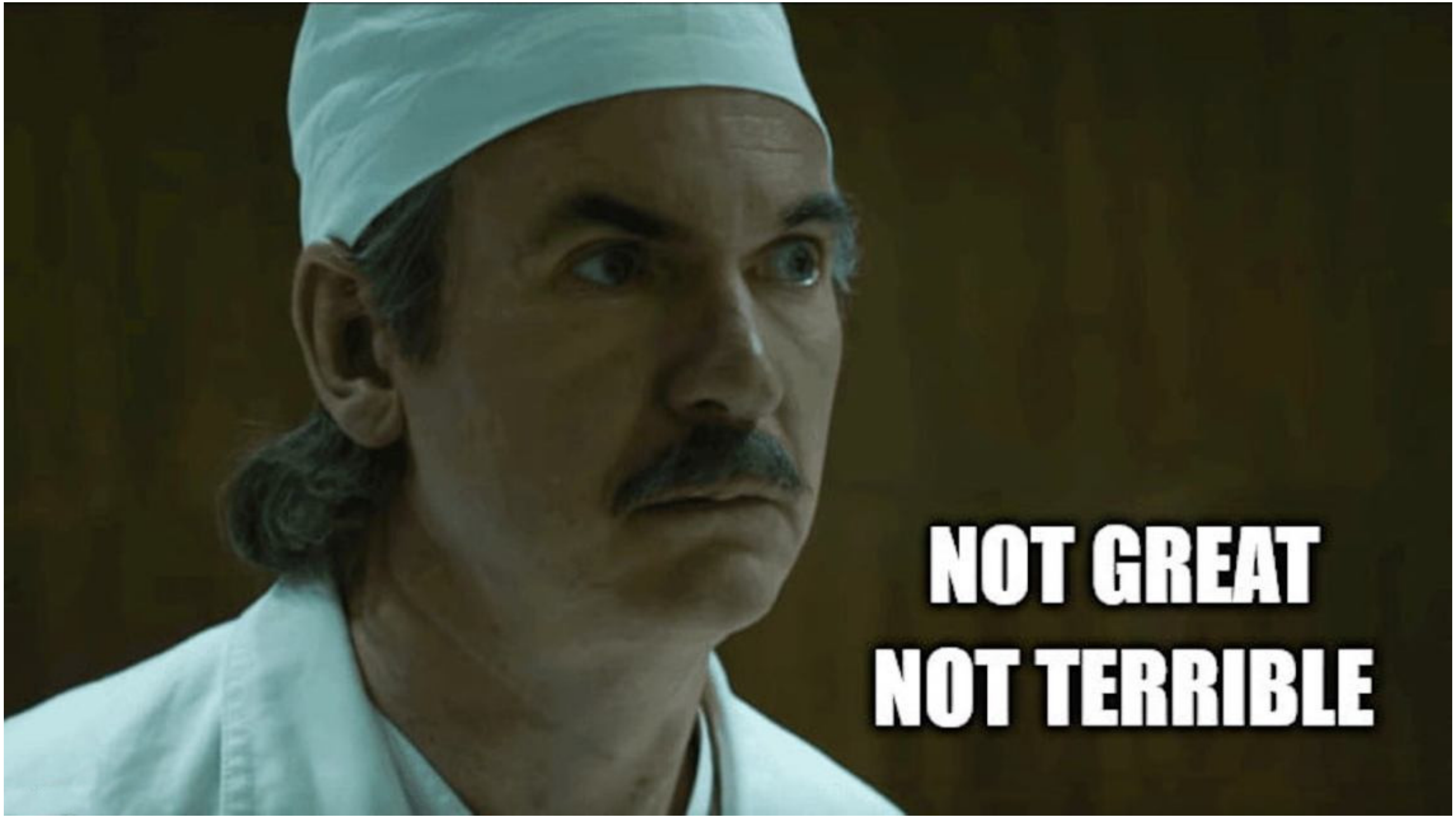


As expected, Gould & Raffelt describes things very well

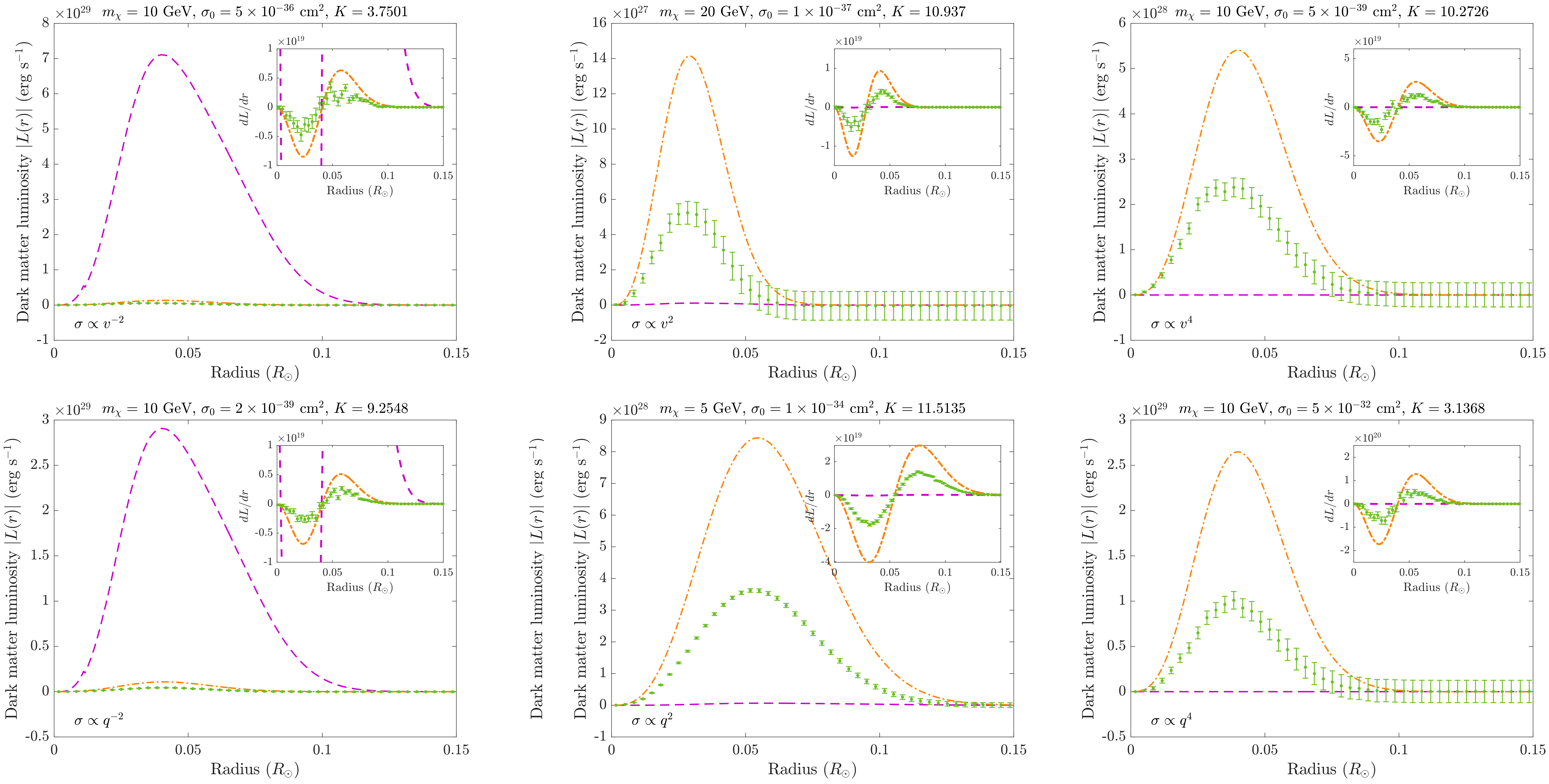
Spergel & Press very wrong because wrong regime

Thanks to Knudsen correction Gould & Raffelt does ok here too

Spergel & Press describes shape better but off by a factor of 2.


NOT GREAT
NOT TERRIBLE

Non-constant cross sections



v^{2n}

q^{2n}

Spergel & Press: Off by a factor of 2

Gould & Raffelt: Off by *a lot*

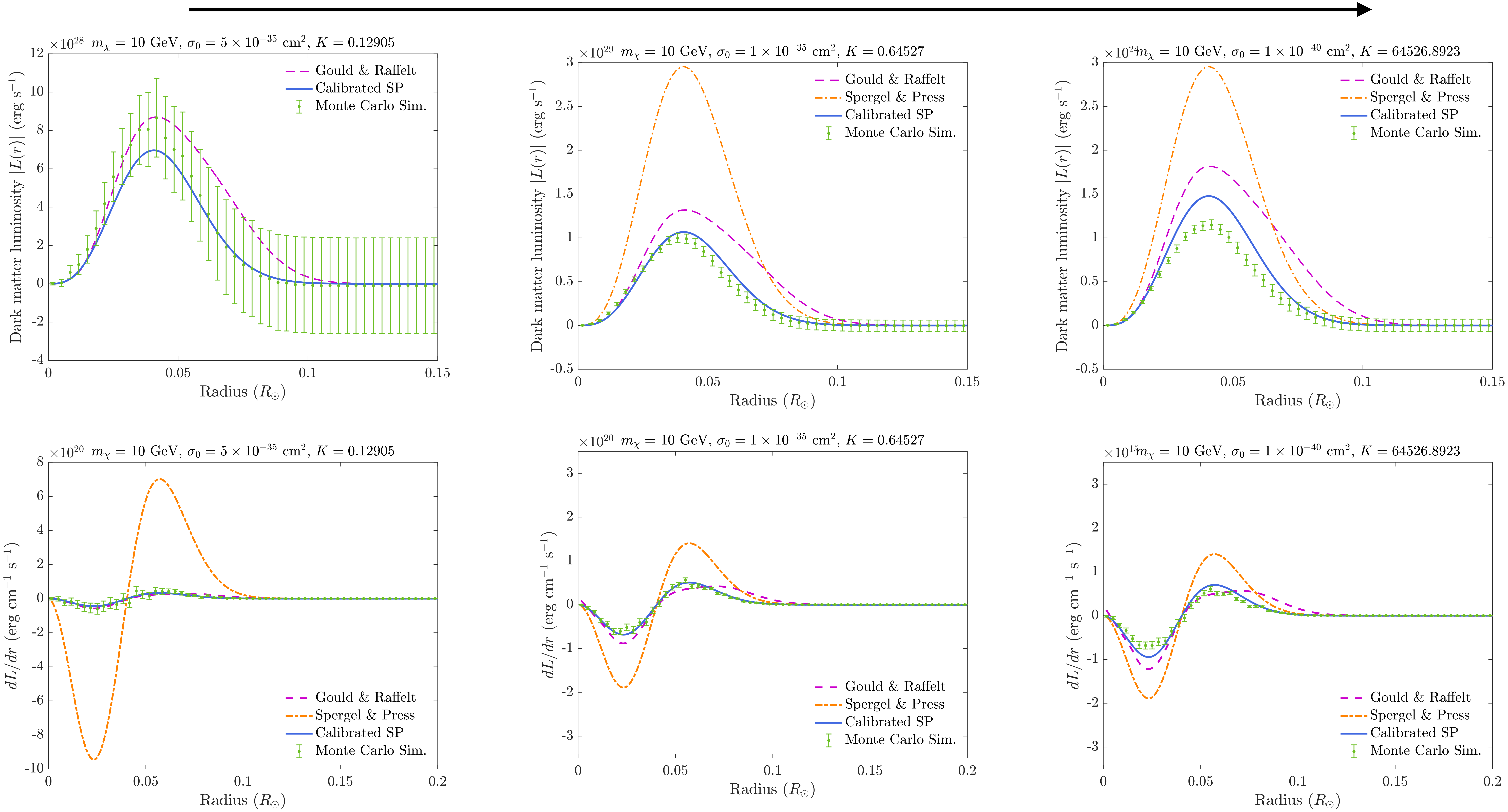
“Calibrated” Spergel & Press approach

$$L(r) = \frac{0.5}{1 + (K_0/K)^2} \times L_{\mathrm{SP}}(r)$$

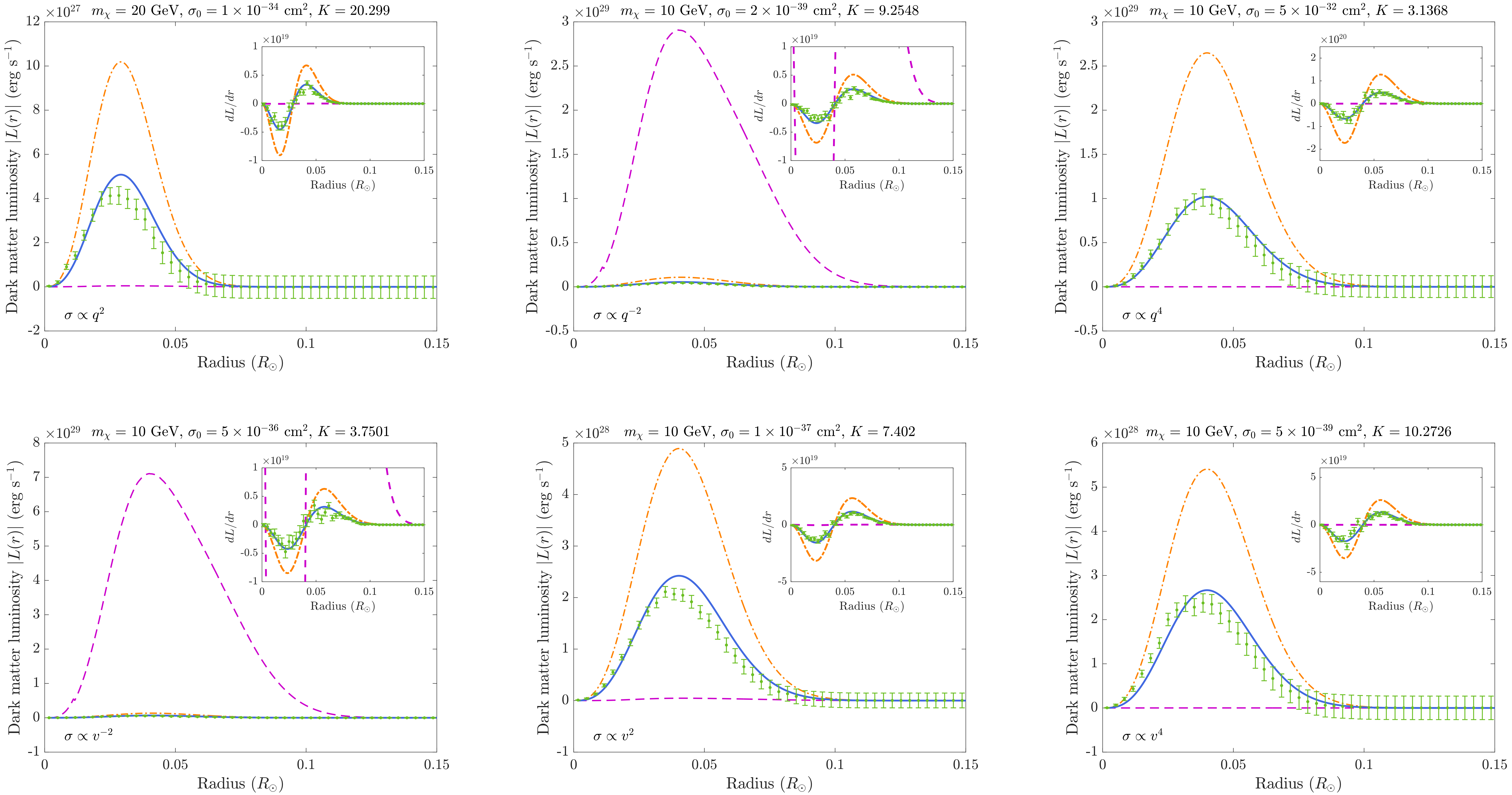
With a simple empirical scaling, the “incorrect” approach is actually much more robust to different models & stellar structures

Banks, Ansari, Scott, ACV 2111.06895

Strong interactions — Knudsen transition — Weak interactions



Banks, Ansari, Scott, ACV 2111.06895



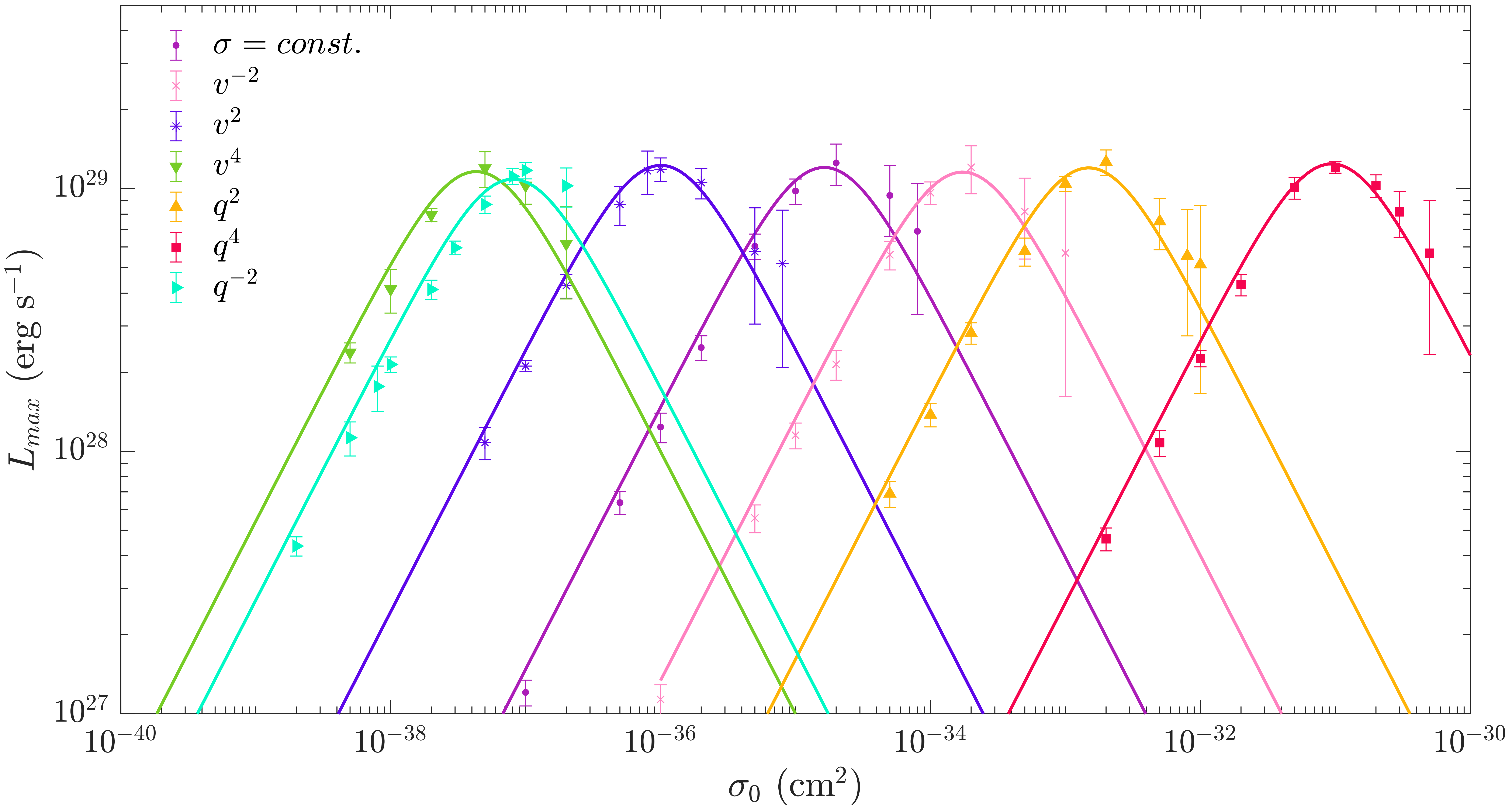
v^{2n}

q^{2n}

Banks, Ansari, Scott, ACV 2111.06895

All models, all cross sections: maximum luminosity

$$L(r) = \frac{0.5}{1 + (K_0/K)^2} \times L_{\rm SP}(r)$$



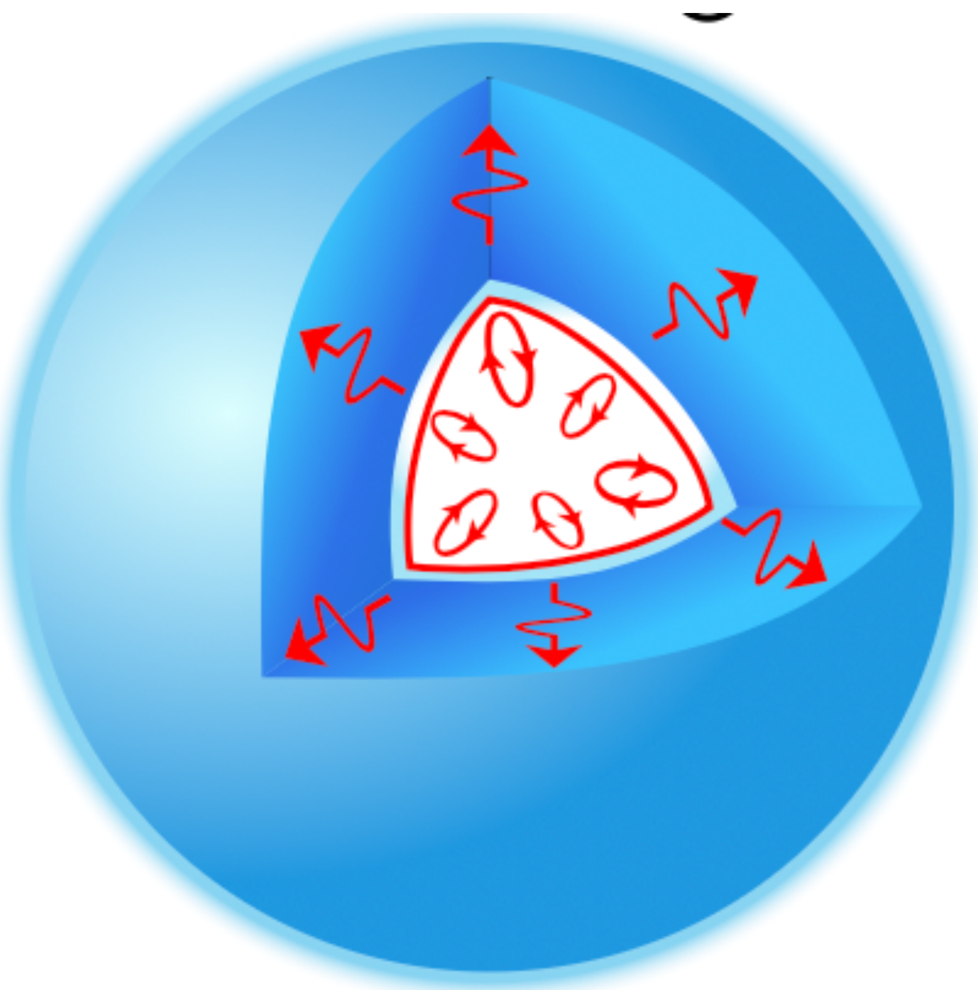
Now ready to go back into stellar simulations

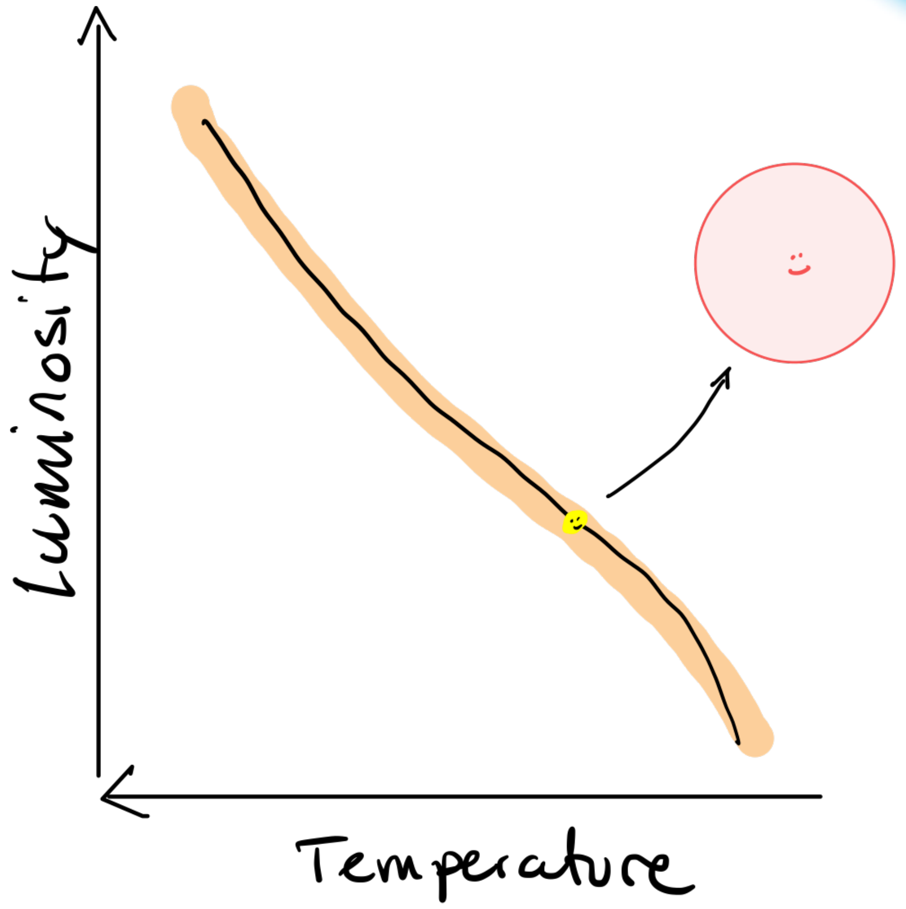
Banks, Ansari, Scott, ACV 2111.06895

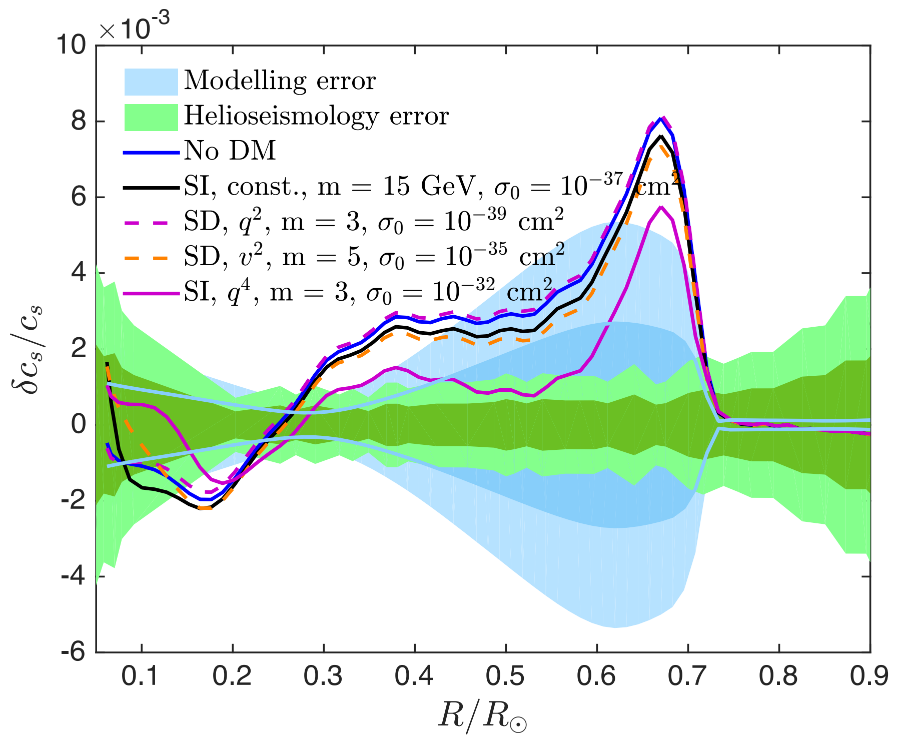
Upgrades

- These results were based on a SHO approximation for the orbits (valid in the centre, and *fast* — no analytic trajectory integrals), and scattering with H only.
- Upgraded ***Cosmion*** code rewritten in Fortran for speed: includes spin-dependent interactions, arbitrary gravitational potentials.
- Scheme looks robust across star and interaction models: our formalism should be robust enough
- Work in progress with Rashaad Reid (Queen's) and Hannah Banks (Cambridge). Results and code soon!

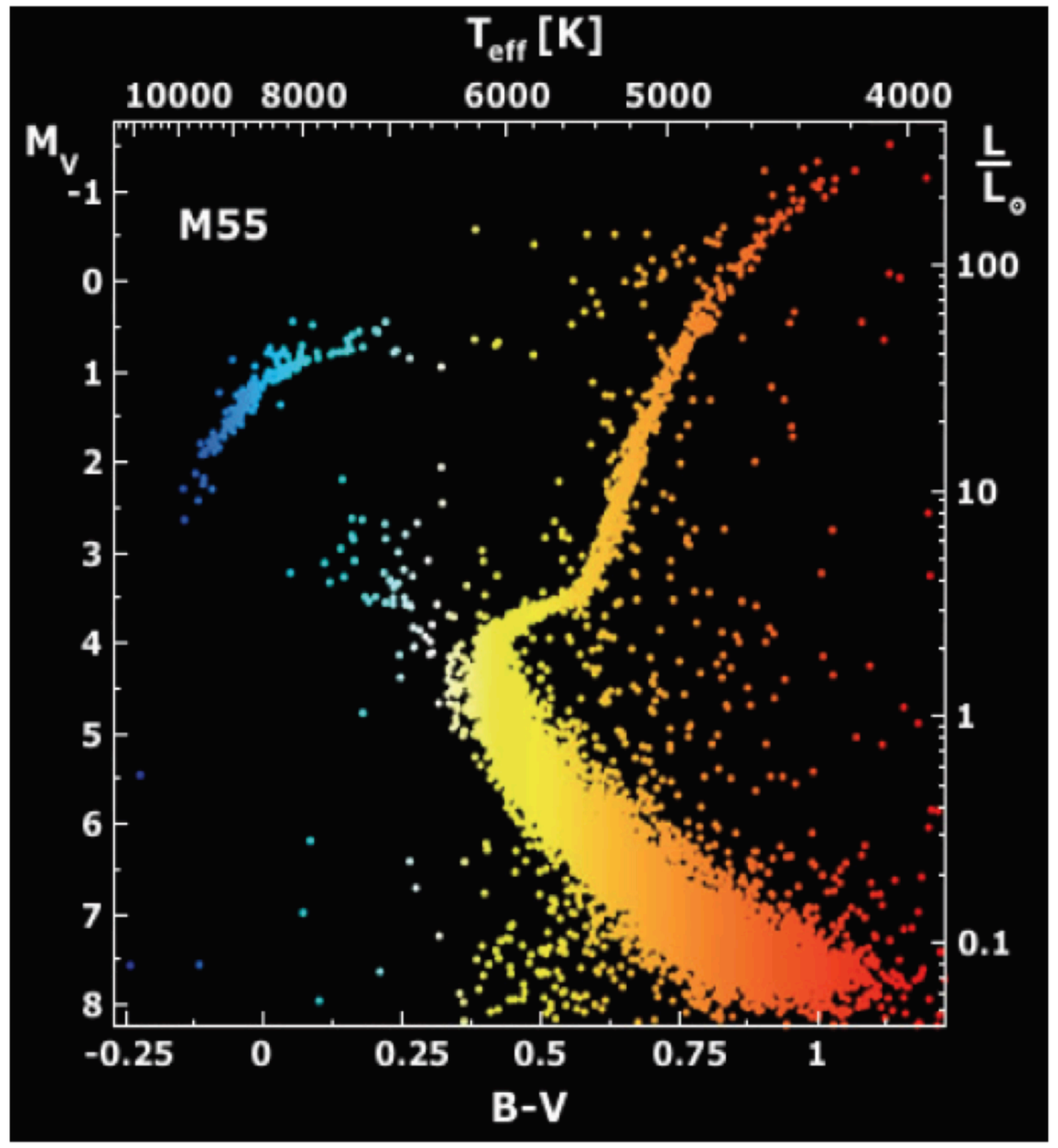
Still a lot of development needed





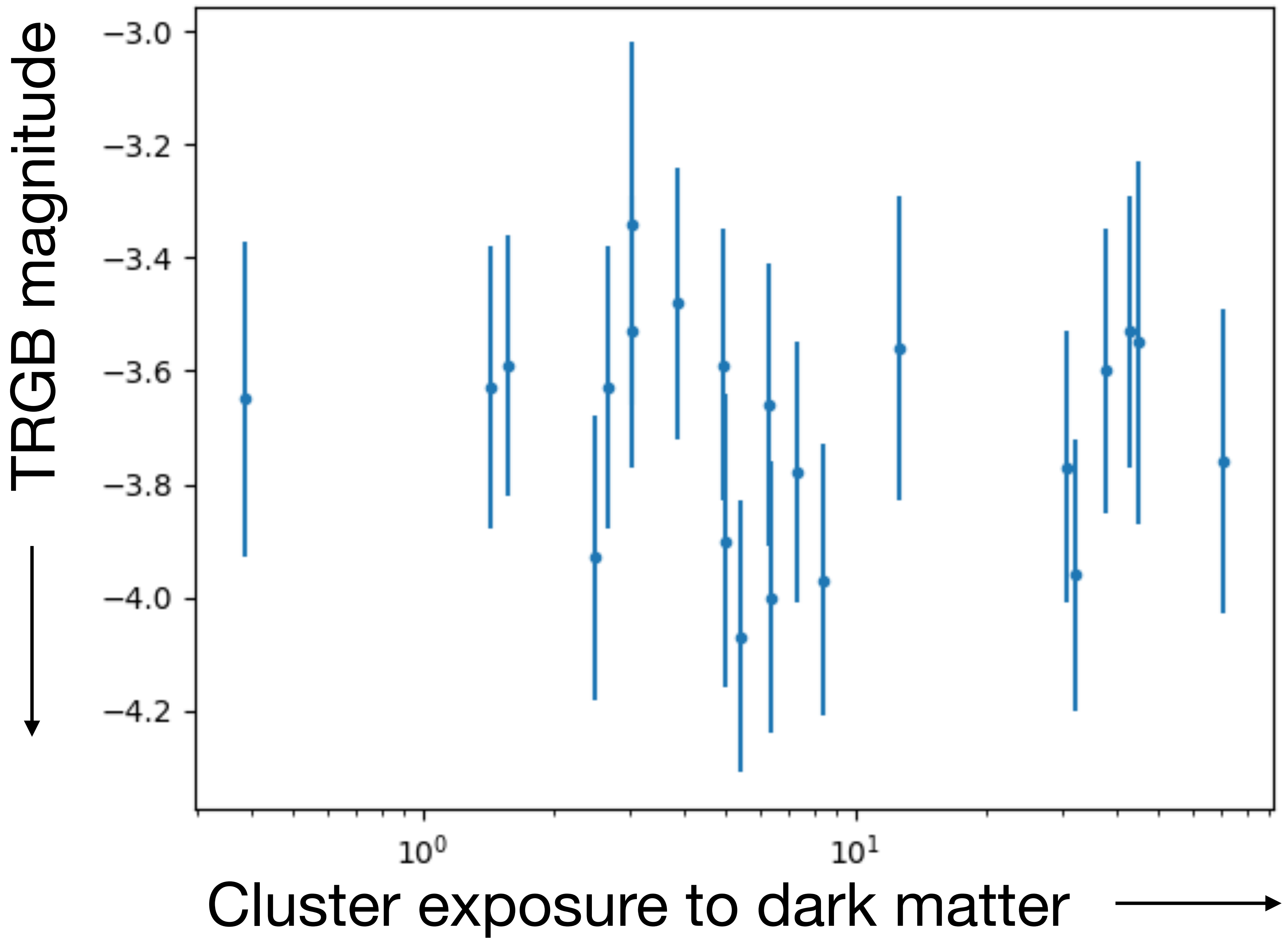


Sound speed



Throw into stellar evolution simulations and see what comes out

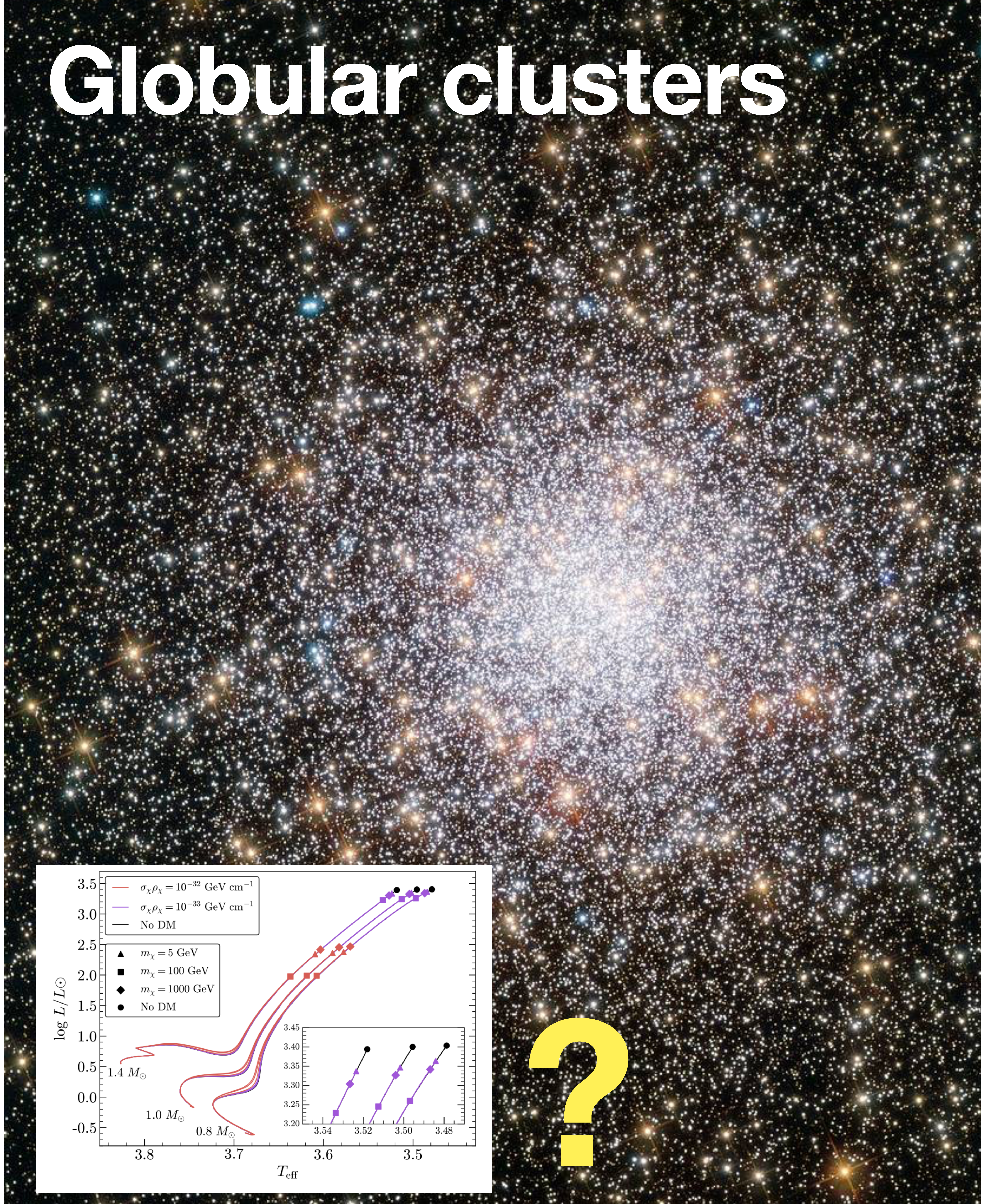
Globular clusters



Work in progress with H. Hong (Queen's) using (mostly) *Gaia* data

TRGB luminosity vs lifetime "exposure" to dark matter — we expect to shrink these error bars & add more clusters

Main Sequence turnoff?

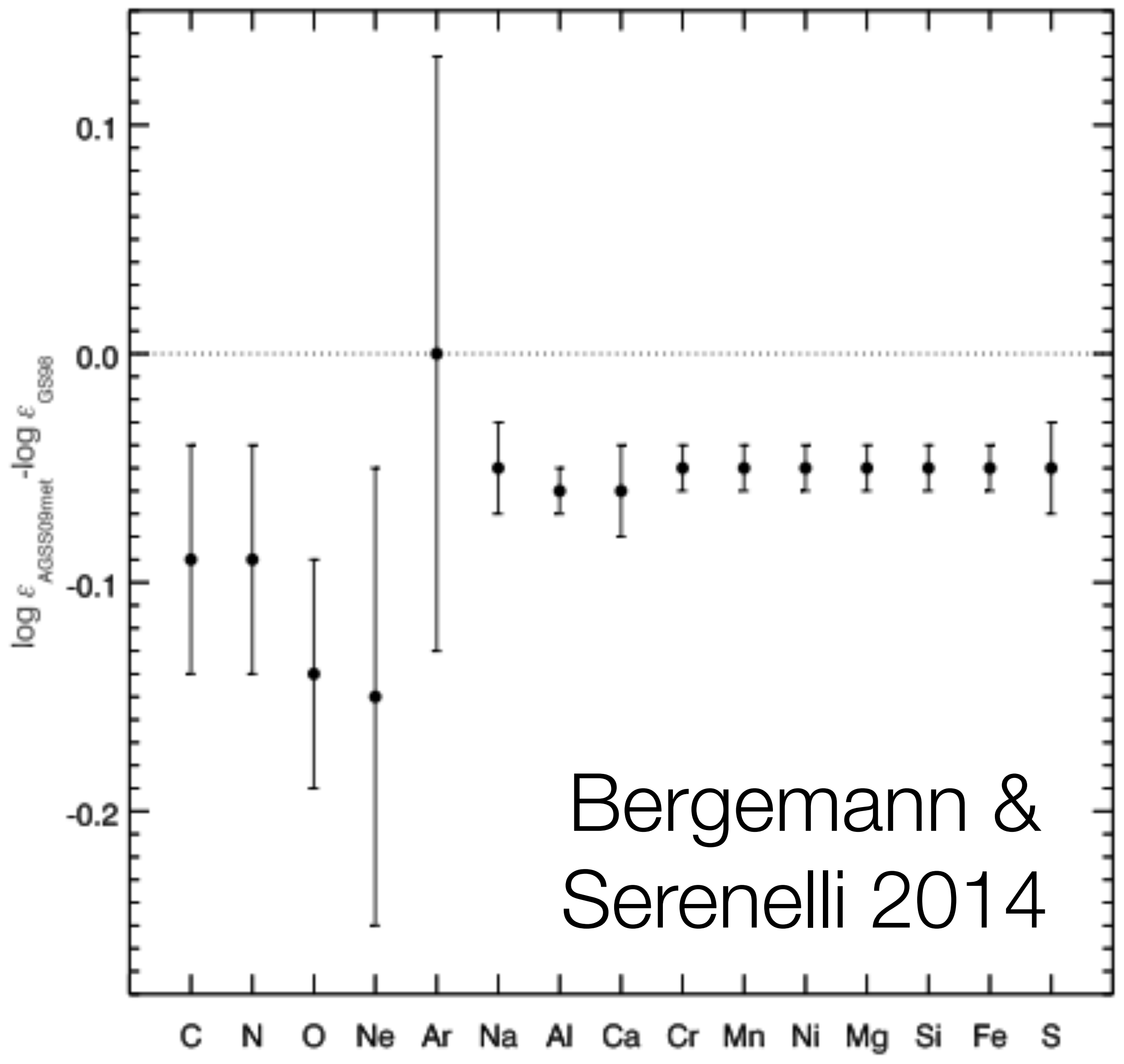


Summary

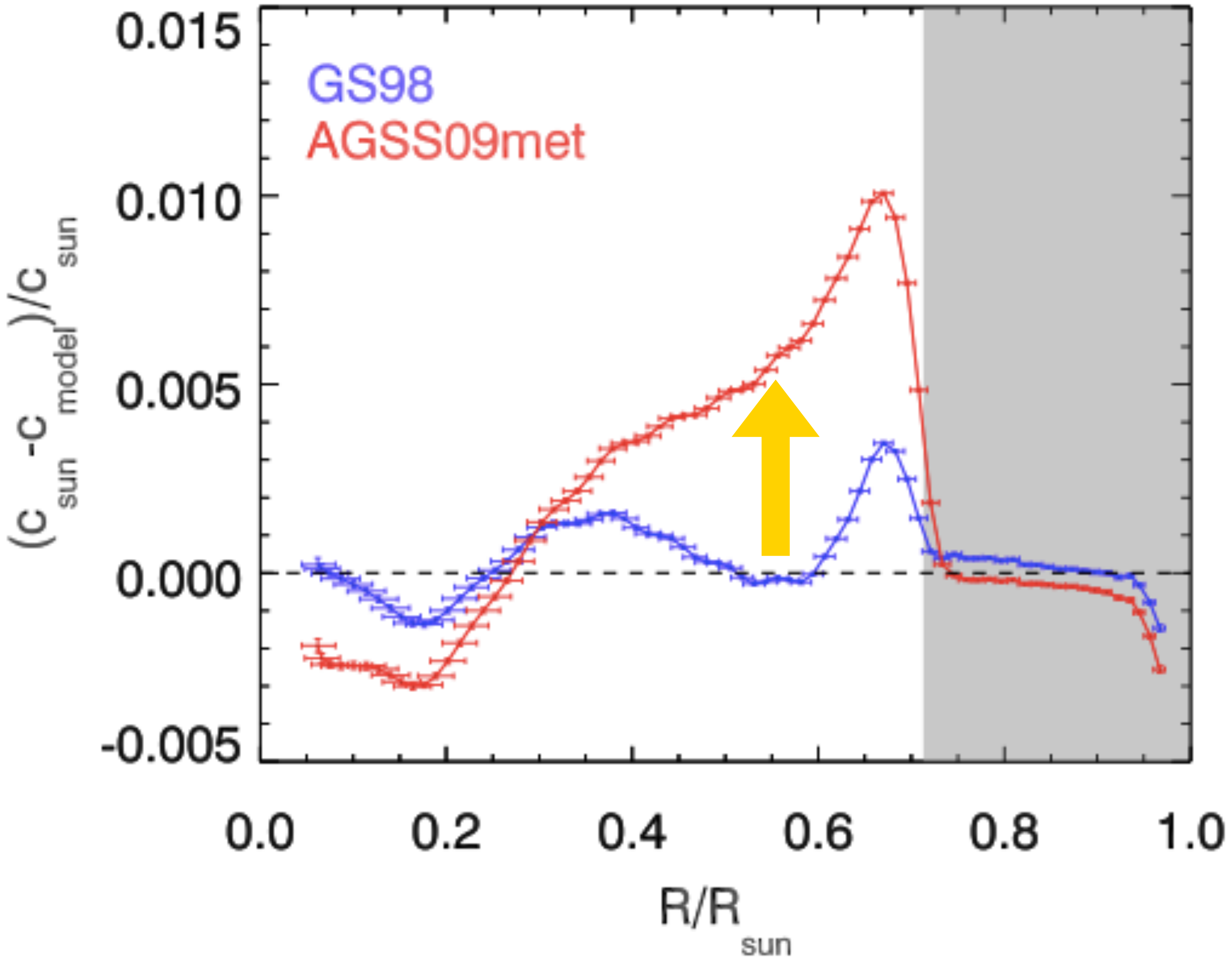
- A direct dark matter-nucleon coupling inevitably leads to capture in stars
- Interesting phenomenology abounds: neutrinos, asteroseismology, the tip of the red giant branch…
- We're only now getting an accurate picture of how heat transport by weakly-interacting particles really affects the fate of stars
- Ongoing work @ Queen's: Solar composition problem (Neal Avis Kozar), DM-electron interaction (Stephanie Beram)
- Competition with direct detection is tough, but this is a complementary: different coupling types, can probe dark matter over/underdensities in the Milky Way.

Extras

Solar composition problem (since 2004)



revised - old abundances

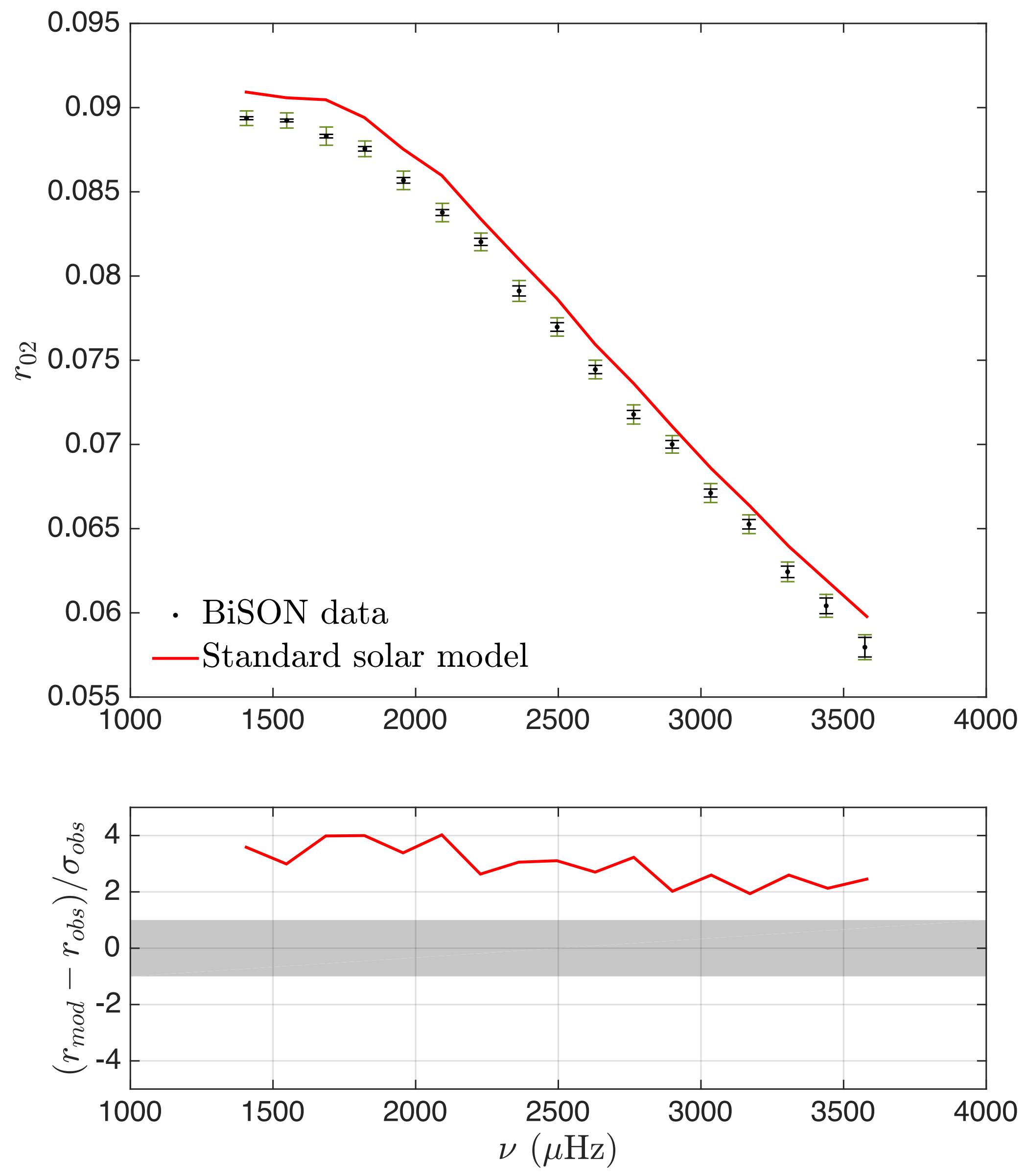


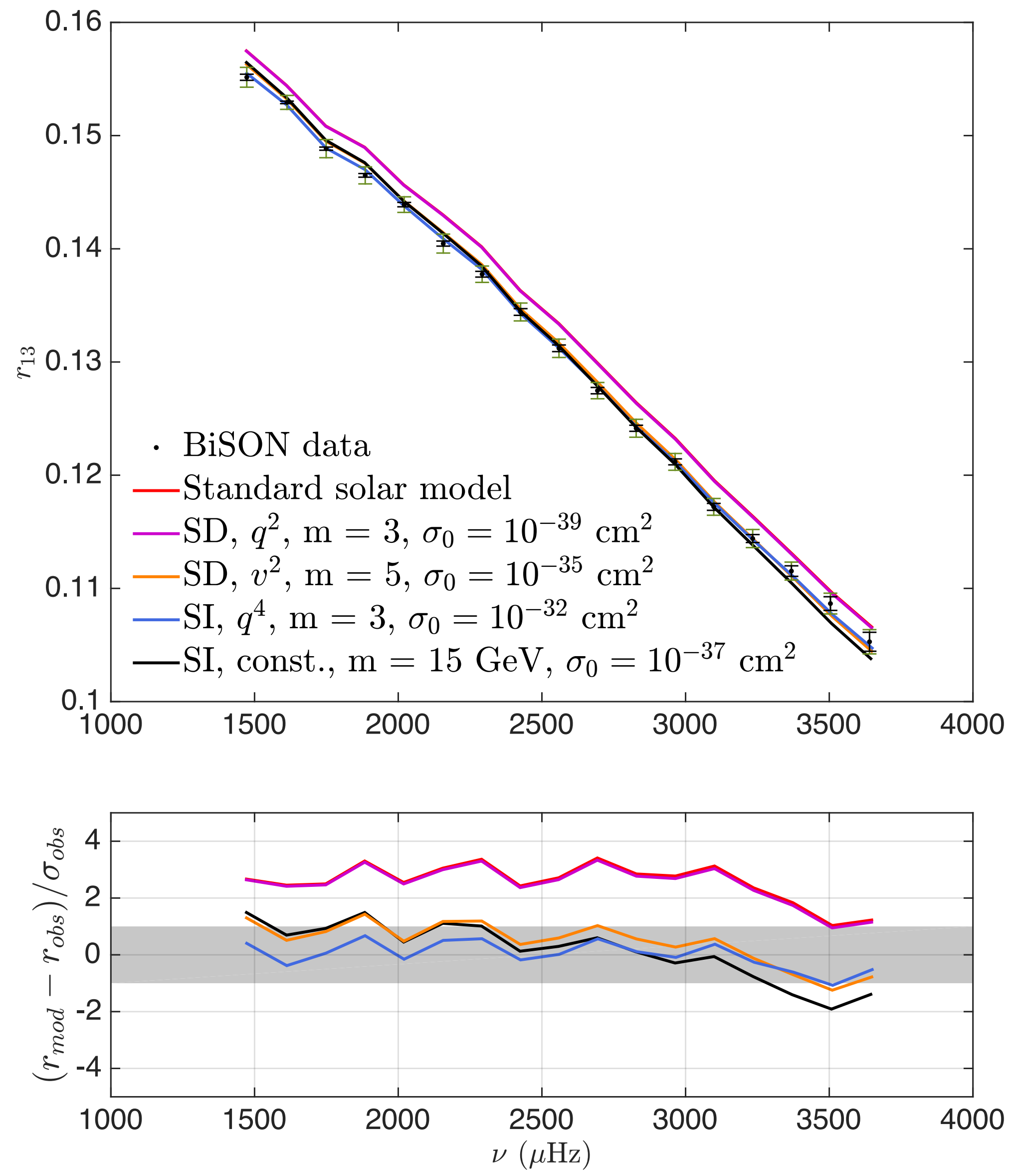
$$R_{\mathrm{CZ},\odot} = 0.713 \pm 0.001\, R_\odot$$
$$R_{\mathrm{CZ,SSM}} = 0.722 \pm 0.004\, R_\odot$$

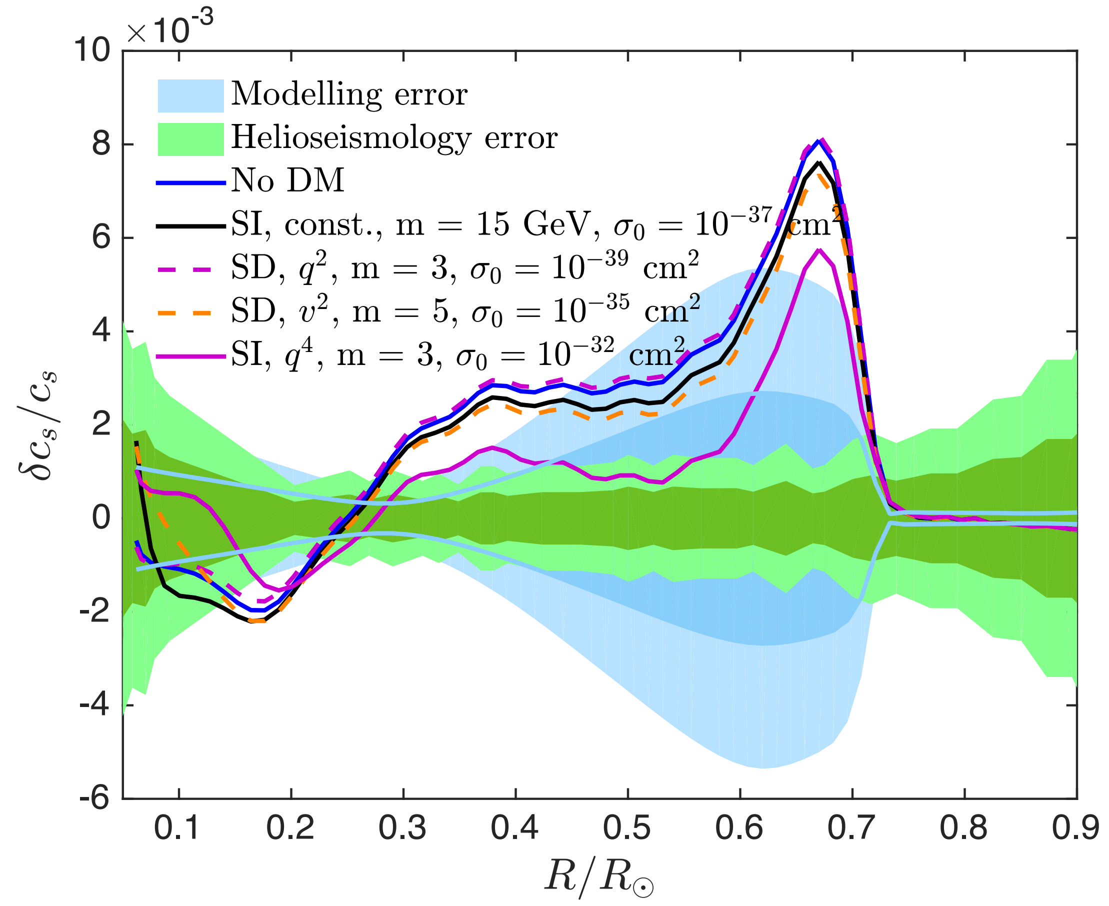
Sound speed off by $\sim 4 - 5\sigma$?

Solar composition problem

Small frequency separations: a probe of the core





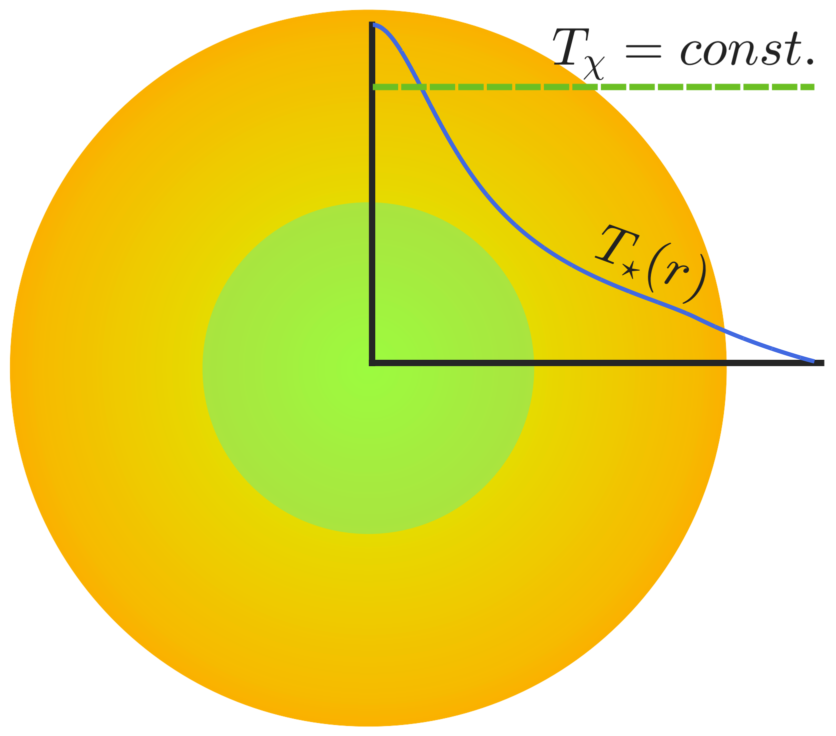


Sound speed

Asymmetric DM may be a solution to the solar composition problem, but as I will discuss in the next section, these results are based on assumptions that may not be true

ACV, Pat Scott, Aldo Serenelli 1411.6626, 1504.04378,1605.06502

Solution method 1: isothermal (Spergel & Press, 1984)



$$DF(\mathbf{v}, \mathbf{r}, t) \simeq 0 \quad \rightarrow F \sim \exp\left(-\frac{\frac{1}{2}mv^2 + m\phi(r)}{kT_\chi}\right)$$

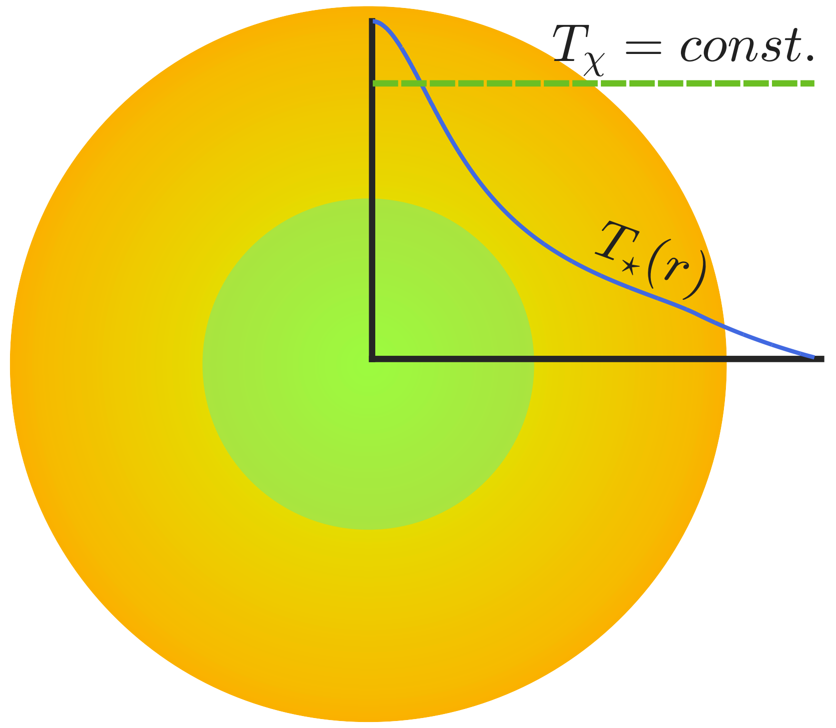
DM is at a single 'average' temperature T_χ

Conduction treated as contact between two weakly coupled heat baths

$$\epsilon \propto \sigma\left(T_\star(r) - T_\chi\right)$$

- Heat removed from star where $T_\star(r) > T_\chi$
- Heat deposited in star where $T_\star(r) < T_\chi$

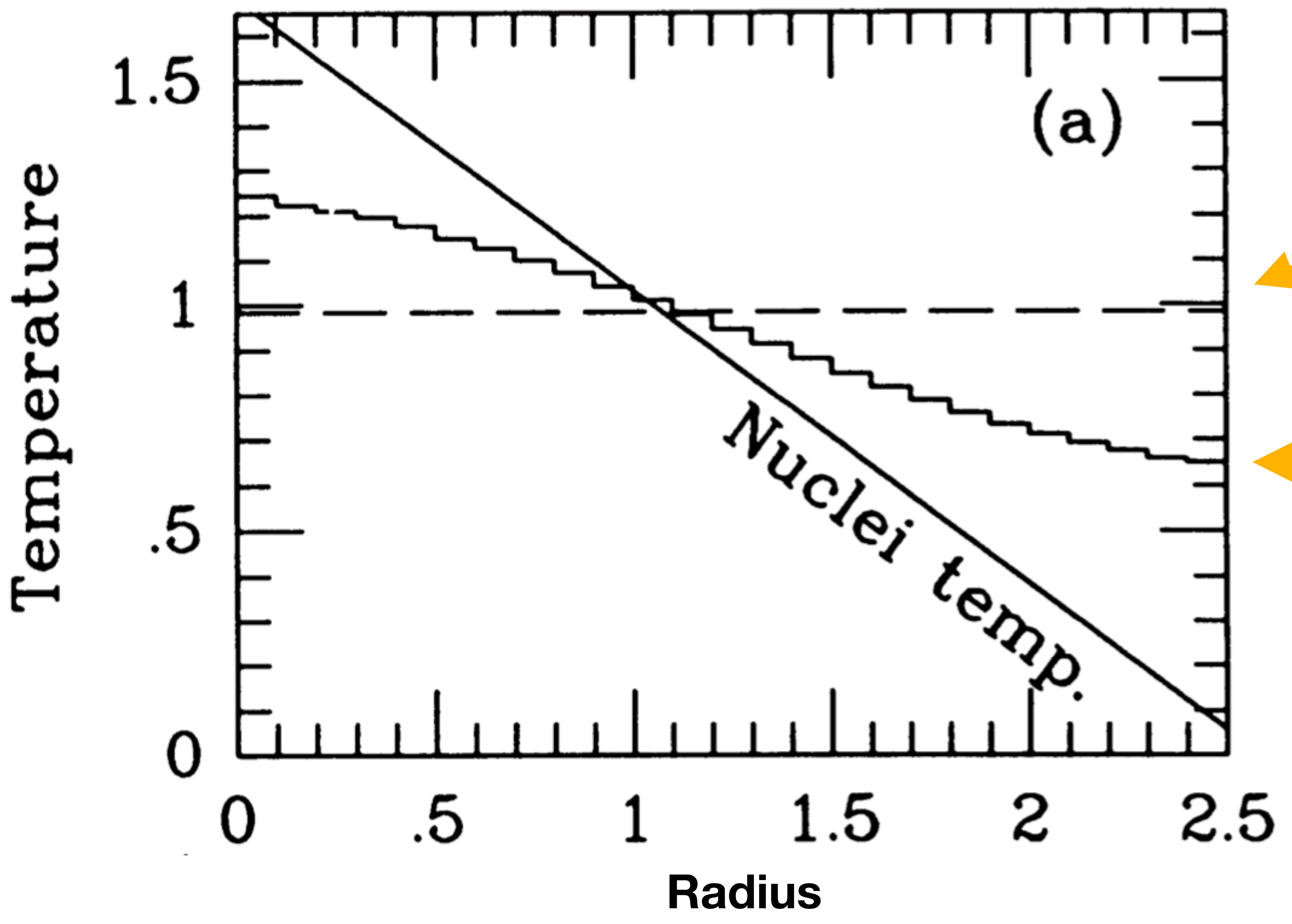
Solution method 1: isothermal (Spergel & Press, 1984)



$$\epsilon \propto \sigma\left(T_\star(r) - T_\chi\right)$$

This has been known to be formally incorrect since 1990, but is still most widely used because it is numerically stable

Gould & Raffelt 1990 Monte Carlo simulation

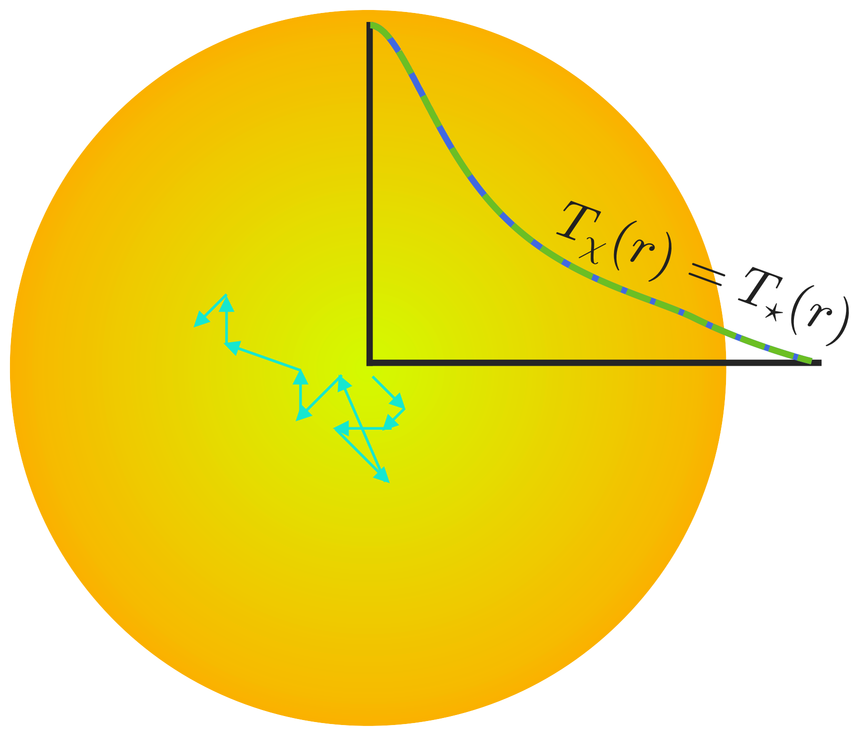


Isothermal assumption T_χ

Actual DM temperature

ΔT overestimated →heat transfer overestimated **by a factor of 2**

Solution method 2: corrected LTE (Gould & Raffelt, 1990)



If $\ell \ll r_\chi$, conduction is **local** $(T_\chi(r) \simeq T_\star(r))$

Expand $DF(\mathbf{v}, \mathbf{r}, t) = \dfrac{1}{\ell_\chi} CF(\mathbf{v}, \mathbf{r}, t)$ in a series in $\ell_\chi |\nabla \ln T_\star|$

Solve first order dipole (only care about radial part)

Distribution

$$n_{\chi,\mathrm{LTE}}(r) = n_\chi(0)\left[\frac{T(r)}{T(0)}\right]^{3/2} \exp\left[-\int_0^r dr' \frac{k_\mathrm{B}\alpha(r')\frac{dT(r')}{dr'} + m_\chi \frac{d\phi(r')}{dr'}}{k_\mathrm{B}T(r')}\right]$$

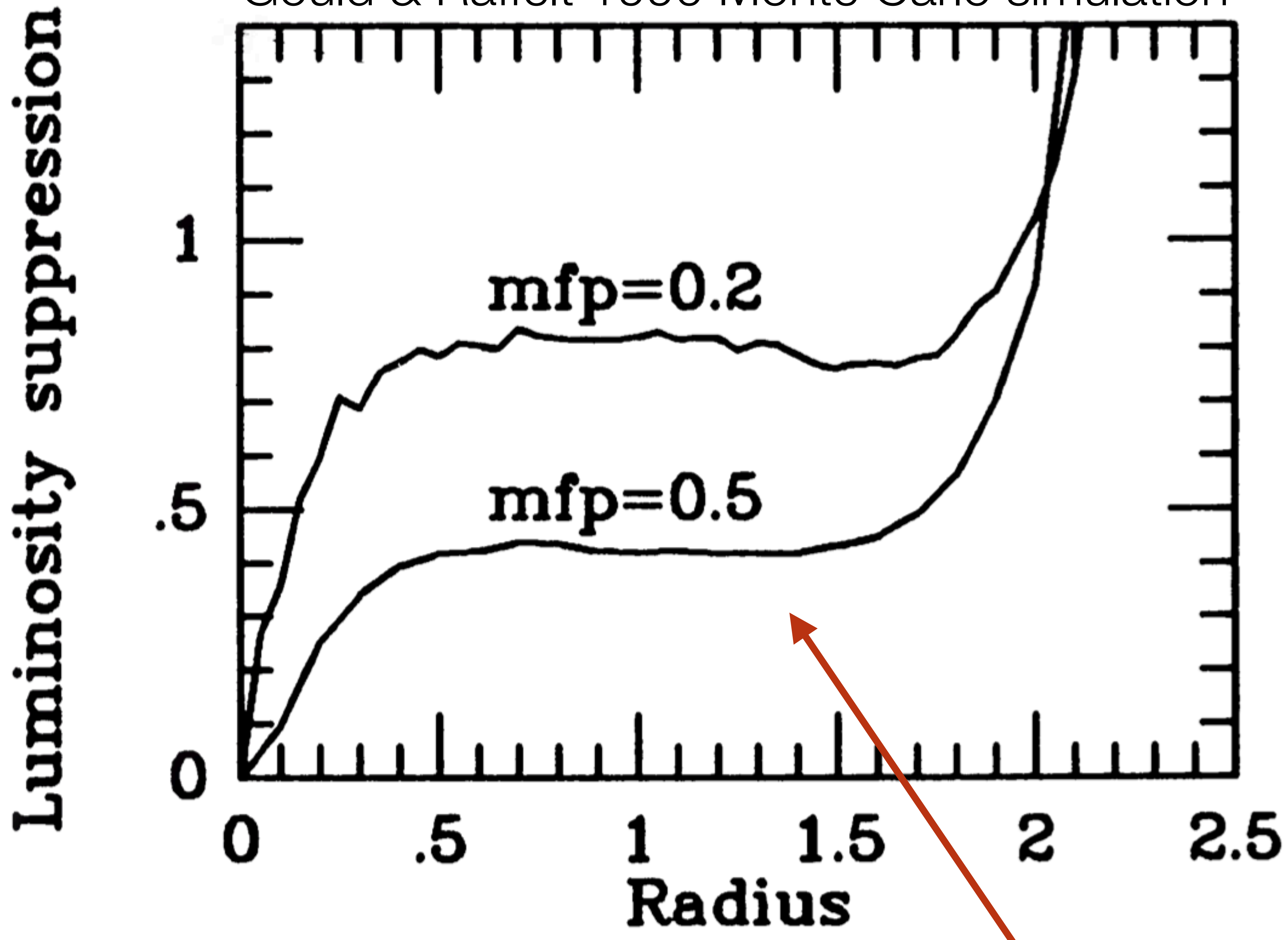
Luminosity

$$L_{\chi,\mathrm{LTE}}(r) = 4\pi r^2 \kappa(r) n_\chi(r) l_\chi(r) \left[\frac{k_\mathrm{B}T(r)}{m_\chi}\right]^{1/2} k_\mathrm{B}\frac{dT(r)}{dr},$$

α and κ only depend on $\dfrac{m_{\text{Dark matter}}}{m_{Nuclei}}$

Solution method 2: corrected LTE (Gould & Raffelt)

Gould & Raffelt 1990 Monte Carlo simulation



Two corrections still needed:

- **Knudsen suppression:** condition $\ell_\chi \ll |\nabla \ln T|^{-1}$ breaks down.
- **Radial suppression**: isotropy assumption breaks down at low radii

All "correct" results in the past 30 years use a fit to this graph to fix the LTE prediction

Additional technical issue: numerically unstable (reason method 1 still used)

Solution method 2: corrected LTE (Gould & Raffelt)

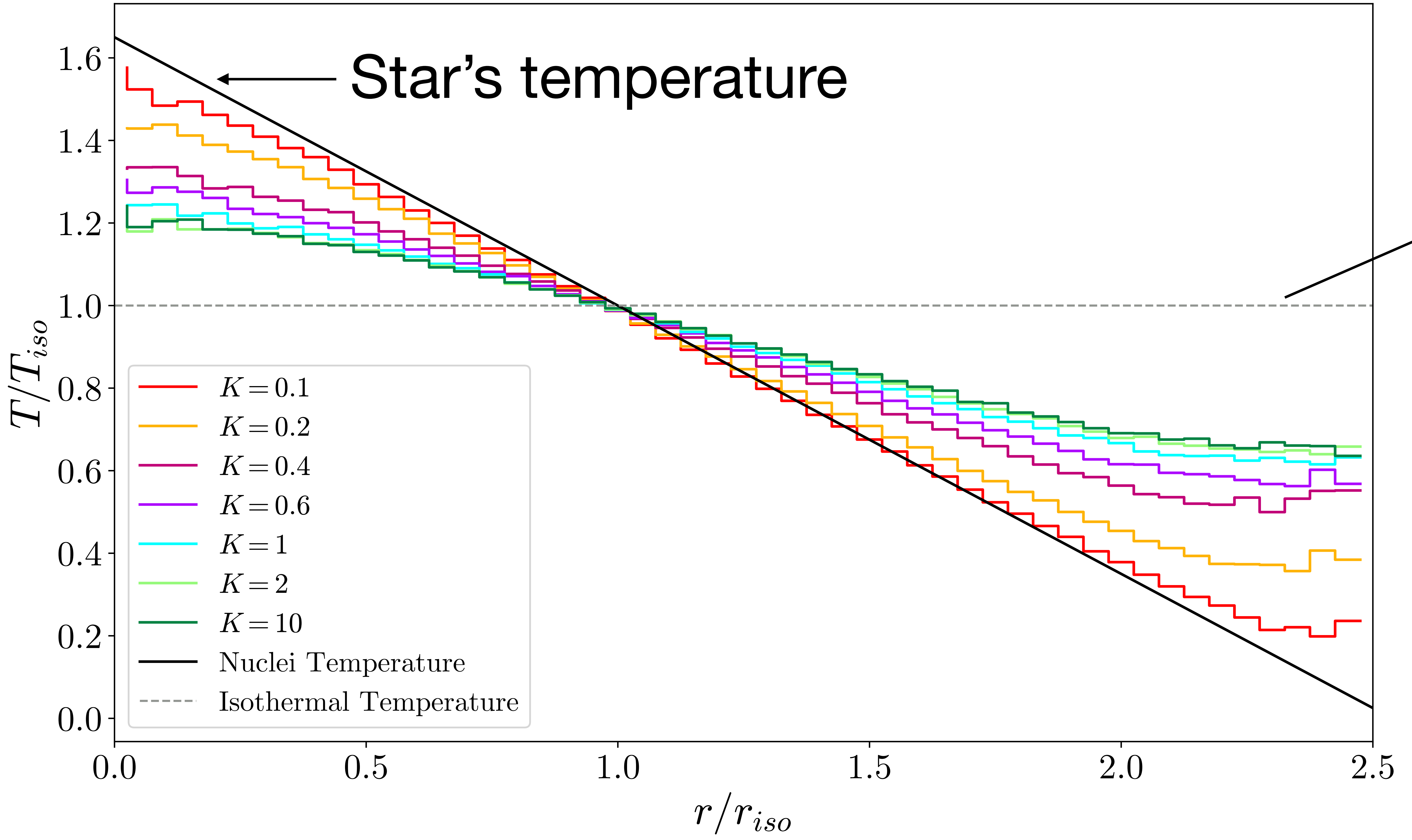
“Correct approach”

LTE (large cross section) approximation
Empirical correction so that it works at small cross sections

Technical detail slide we can skip because I am already running low on time

- Two sets of simulations: Idealized (match gould & Raffelt), Realistic (real sun density, Temperature, but harmonic oscillator potential)
- Match results by G&R
- Simulations across different K (Idealized), different cross sections (realistic)
- Spin-Dependent scattering only (i.e. interactions only with Hydrogen). SI should generalize straightforwardly.
- Zillions of CPU hours.

Dark matter temperature

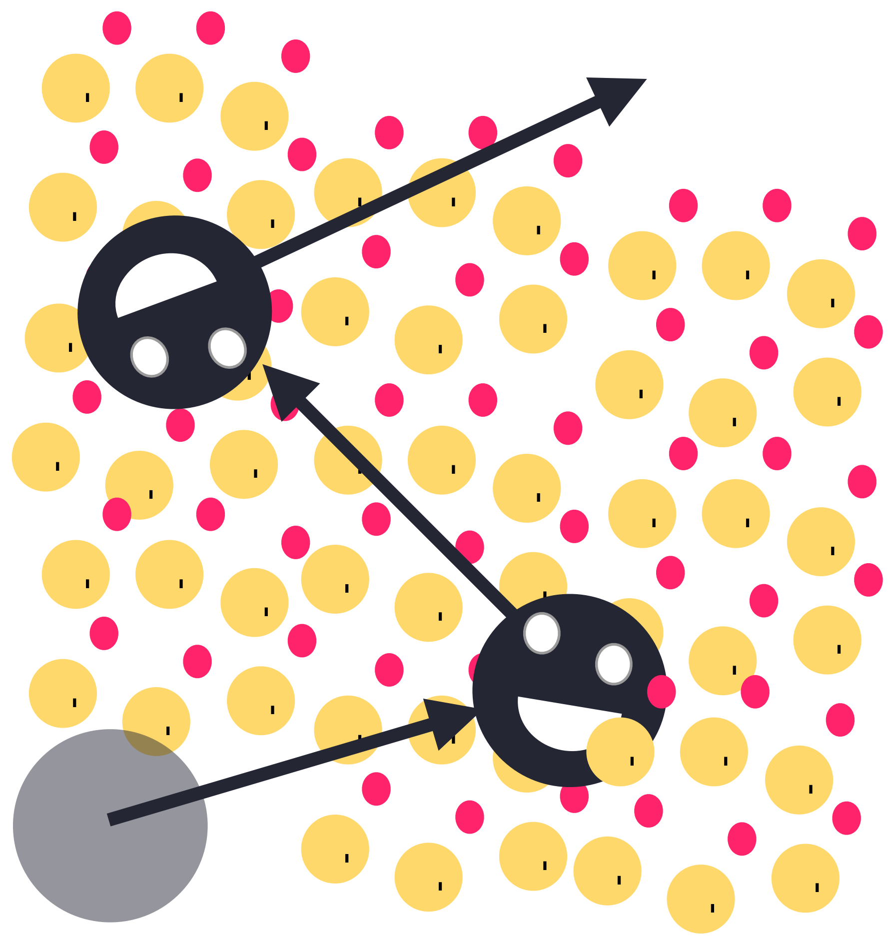


Never quite reaches isothermal temperature: isothermal assumption never quite realized

Decreasing cross section

Non-constant cross sections

Generically $\sigma = \sigma(s, t, u) \to \sigma(\vec{v}_{rel}, \vec{q})$



E.g. ‟ billiard ball”

1/r force

Non-constant cross sections

$$\sigma \propto \sigma_0 q^{2n}$$

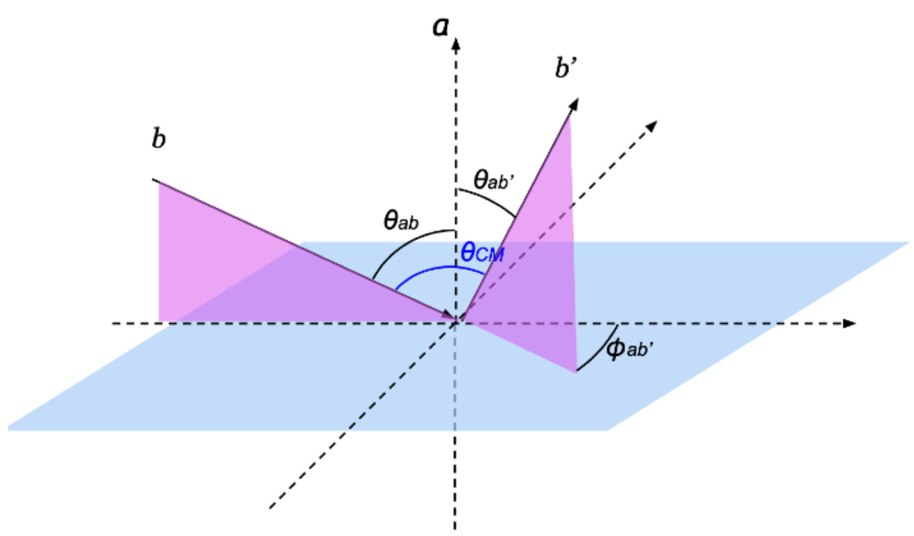
$$\sigma \propto \sigma_0 v^{2n}$$

Gould & Raffelt

Recompute α, κ by inverting new collision operator

$$\alpha_0 = \frac{\langle y|C^{-1}|y^3 f_0^{0,0}\rangle}{\langle y|C^{-1}|y f_0^{0,0}\rangle}.$$

$$\kappa = \frac{\sqrt{2}}{3}\langle y^3|f_1^{1,0}\rangle$$



Vincent & Scott 2013

Spergel & Press

Recompute thermal averages

$$\epsilon_{\rm SP} = \frac{8}{\rho(r)}\sqrt{\frac{2}{\pi}}\frac{m_\chi m_N}{(m_\chi + m_N)^2} n_\chi(r) n_N(r) \sigma_{\rm tot} k_B \left(T_\chi - T(r)\right)\left(\frac{k_B T(r)}{m_N} + \frac{k_B T_\chi}{m_\chi}\right)^{\frac{1}{2}}.$$

$$\epsilon = \frac{A_{2n}}{\rho(r)}\sqrt{\frac{2}{\pi}}\frac{m_\chi m_N}{(m_\chi + m_N)^2} n_\chi(r) n_N(r)(1-Q)\sigma_{\rm tot} k_B \left(T_\chi - T\right)\left(\frac{k_B T}{m_N} + \frac{k_B T_\chi}{m_\chi}\right)^{\frac{1}{2}+n}$$

This work (2021)